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MINIMIZING AND MANAGING POTENTIAL IMPACTS OF INDUCED-SEISMICITY FROM CLASS II DISPOSAL WELLS: PRACTICAL APPROACHES

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US Environmental Protection Agency
Washington, DC

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EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) Underground Injection Control (UIC) program regulates injection of fluids related to oil and gas production as Class II injection wells for the protection of underground sources of drinking water (USDW). Unconventional resources and new technologies, such as horizontal drilling and advanced completion techniques, have expanded the geographic area for oil and gas production activities resulting in a need for Class II disposal wells in some areas previously considered unproductive.

Recently, a number of low to moderate magnitude (<5.0) earthquakes1 were recorded in areas with Class II disposal related to shale hydrocarbon production. To address the concern that induced seismicity could interfere with containment of injected fluids and endanger drinking water sources, EPA's Drinking Water Protection Division requested the UIC National Technical Workgroup (NTW) develop a report with practical tools for UIC regulators to address injection-induced seismicity. This report used the existing Class II regulatory framework to provide possible strategies for managing and minimizing the potential for significant[2] injection-induced seismic events. The report focused on Class II disposal operations and not enhanced oil recovery wells or hydraulically fractured wells using diesel, as disposal wells have been suspected of inducing seismicity, including new geographic areas with oil and gas production activities resulting in a need for Class II disposal. Of the approximately 30,000 Class II disposal wells in the U.S., very few (<10) disposal well sites have produced seismic events with magnitudes greater than M 4.0 and none being greater than M 5.0[3]. In formulating these strategies, the NTW conducted a technical literature search and review. Additionally, the NTW evaluated four case examples (Arkansas, Ohio, Texas and West Virginia) and considered data availability, and variations in geology and reservoir characteristics. EPA is unaware of any USDW contamination resulting from seismic events related to injection induced seismicity.

Commented [A1]: Added based on R5 comment

Commented [A2]: Added based on R8 cmt

Disposal wells are one of a number of historic causes of human activity-induced earthquakes. Others include construction of dams and water reservoirs, mining activities, oil and gas production, and geothermal energy production. Evaluation of induced seismicity is not new to

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[1] Information on earthquake terms is included under *Glossary terms* or http://earthquake.usgs.gov/earthquakes/glossary.php for terms used in USGS maps; http://earthquake.usgs.gov/learn/glossary/ for general earthquake terms

[2] For the purposes of this report, the Induced Seismicity Working Group considers "significant" seismic events to be those of magnitude to potentially endanger underground sources of drinking water.

[3] Chapter 3, Table 3.4, page 104, and Chapter 7, Injection Wells for the Disposal of Water Associated with Energy Extraction Finding No. 1, pages 171-172; "Induced Seismicity Potential in Energy Technologies," 2013 NAS Publication.

the UIC program. This report is intended to describe for UIC program management the current understandings related to induced seismicity within the existing Class II regulatory framework for Class II disposal. The Class II UIC program does not have regulations specific to seismicity but rather includes discretionary authority that allows additional conditions to be added to the injection permit on a case-by-case basis as well as additional requirements for construction, corrective action, operation, monitoring, or reporting (including closure of the injection well) as necessary to protect USDWs.[4] Legal and policy considerations of Class II regulations, including regulatory revisions, are outside the scope of this technical report. This report is not a guidance document and does not provide specific procedures, but does provide Director with considerations for addressing induced seismicity on a site specific basis, using Director discretionary authority.

The NTW confirmed the following components are necessary for significant injection-induced seismicity: (1) critically stressed faults[5], (2) pressure buildup from disposal activities, and (3) a pathway for increased pressure to communicate with the fault. The NTW noted that no single recommendation addresses all of the complexities related to injection-induced seismicity, which is dependent on a combination of site geology, geophysical and reservoir characteristics. An absence of historical seismic events in the vicinity of a disposal well does not provide assurance that induced seismicity will not occur; however, this absence may be an indicator of induced seismicity if events occur following activation of an injection well, assuming there is an accurate history of seismic monitoring in the region of the injection well. Conclusive proof of induced seismicity is difficult to achieve, but it is not a prerequisite for prudent action.

The NTW developed a decision model (Figure 1) to inform UIC regulators about site assessment strategies and practical approaches for assessing the three fundamental components. The model begins with considerations for a site assessment dependent on location specific conditions, because understanding the geologic characteristics of a site is an essential step in evaluating the potential for injection-induced seismicity. Monitoring, operational and management approaches with useful practical tools for managing and minimizing injection-induced seismicity are recommended. The NTW also found that basic petroleum reservoir engineering practices coupled with geology and geophysical information can provide a better understanding of reservoir and fault characteristics and offer many ways of analyzing injection-induced seismicity concerns, possibly identifying anomalies that warrant additional site assessment or monitoring. This understanding would be enhanced by collaborative work

Commented [A3]: Added based on Warpinski cmt

Commented [A4]: Added based on Satterfiled cmt

Commented [A5]: R8 cmt

Commented [A6]: Added based on SMU cmt

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[4] 40 CFR §144.12(b); 40 CFR §144.52(a)(9); or appropriate section of 40 CFR Part What about 144.52(b)(1)?

[5] Critically stressed fault as used in this report denotes a fault that is favorably oriented with the potential to cause a significant earthquake. Fault may refer to a single or a zone of multiple faults and fractures.

between a wide variety of individuals in industry, government and research. This is particularly the case for combining earthquake seismology, a field with theory developed principally in academia with observations and operations by civil authorities, with reservoir engineering, exploration geology, and geophysics developed principally in industry. The NTW recommends that future research consider a practical multidisciplinary approach and a holistic assessment addressing disposal well and reservoir behavior, geology, and area seismicity.

Commented [A7]: R8 cmt

INTRODUCTION

The Environmental Protection Agency (EPA) Underground Injection Control (UIC) program, authorized by the Safe Drinking Water Act, regulates injection of fluids related to oil and gas production into Class II wells, for the protection of underground sources of drinking water (USDW). There are approximately 30,000 Class II disposal wells in the U.S. used to dispose of oil and gas related wastes, many of which have operated for decades. Very few (<10) of these disposal well sites have produced seismic events with magnitudes[6] greater than M 4.0 and none being greater than M 5.0[7]. EPA is also unaware of any USDW contamination resulting from seismic events related to injection induced seismicity. For example, there are approximately 5,000 active disposals wells in Kansas with no recent significant[8] seismic events occurring as a result of the disposal activities[9]. However, unconventional resources and new technologies, such as horizontal drilling and advanced completion techniques, have increased oil and gas production activities resulting in a need for additional Class II disposal wells in expanded geographic areas.

Disposal wells are one of a number of historic causes of human activity-induced earthquakes[10]. Others include construction of dams and water reservoirs, erection of skyscrapers, mining activities, oil and gas production, geothermal energy production, and geologic carbon sequestration.

Commented [A8]: Add about more fundamentals and detail in appendices

Commented [A9]: Changed based on R8 cmt

Commented [A10]: Added to address cmts clarifying there has been no USDW contamination. (Satterfield/Warpinski cmts)

Commented [A11]: Added based on Warpinski cmt

Commented [A12]: R8 cmt

ENHANCED OIL RECOVERY INJECTION WELLS

Class II injection wells include injection for the purpose of enhanced oil recovery or oil and gas production wastewater disposal. Injection related to enhanced recovery projects generally poses less potential to induce seismicity than a brine disposal well because pressure changes resulting from injection and production volumes partially offset each other during enhanced recovery. Given the greater potential for pressure buildup and recent seismic activity, both associated with Class II disposal wells, this WG effort focused on recommendations to manage or minimize induced seismicity associated with oil and gas related Class II disposal wells.

Commented [A13]: SMU recommended including a reference

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[6] Magnitude will refer to the values reported by USGS Advanced National Seismic System

[7] Chapter 3, Table 3.4, page 104, and Chapter 7, Injection Wells for the Disposal of Water Associated with Energy Extraction Finding No. 1, pages 171-172; "Induced Seismicity Potential in Energy Technologies," 2013 NAS Publication.

[8] For the purposes of this report, the Induced Seismicity Working Group considers "significant" seismic events to be those of magnitude to potentially endanger underground sources of drinking water.

[9] KCC active C2D well count was 4998 on September 10, 2013

[10] on earthquake terms is included under *Glossary terms or* http://earthquake.usgs.gov/earthquakes/glossary.php for terms used in USGS maps; http://earthquake.usgs.gov/learn/glossary/ for general earthquake

Hydraulic Fracturing

Although not the emphasis of this effort, seismicity associated with HF was addressed by a review of selected literature sources. The Working Group agrees with the conclusions that HF has a low likelihood of inducing significant seismicity.

Unlike disposal wells that inject for an extended period of time, hydraulic fracturing (HF) is a short-term event designed to create cracks, or permeable avenues, in low permeability hydrocarbon-bearing formations. HF activity is followed by the extraction of reservoir fluids and a decrease in pressure within the formation. Therefore, the "pressure footprint" of a well that has been hydraulically fractured is typically limited to the fracture growth or fracture propagation area (Gidley et al., 1990). In comparison, Class II disposal wells typically inject for months or years and generate large "pressure footprints" with no offset production of fluids. The intent of HF is designed to crack the rock formation to enhance production. HF process causes microseismic events that generally are not felt ($\leq$ 2.5 magnitude) at the surface. Several studies documented microseismicity (magnitude < 1) caused by HF (Das and Zoback, 2011; Phillips et al., 2002; Warpinski, 2009 and 2012). Recording these very low magnitude seismic events (microseismicity) requires the use of downhole seismometers in nearby wells (Warpinski, 2009). Though rare, felt HF induced seismicity is possible if the HF encounters a critically stressed fault. Documented cases list seismic events up to magnitude 3.8 due to HF communication with optimally oriented, critically stressed faults (BC Oil and Gas Commission, 2012; de Pater and Baisch, 2011; Holland, 2011 and 2013, Kanamori and Hauksson, 1992.

Geothermal Injection Wells

A number of informative references on induced seismicity and enhanced geothermal systems exist that cover a broad range of issues and outline many avenues of additional research needed (Hunt and Morelli, 2006; Majer et al., 2007; and Majer et al., 2011). These authors documented the combination of monitoring techniques with operational parameters to control seismicity. For example, thermal stress, in addition to pressure buildup, plays a key role in geothermal seismicity and may be applicable to brine disposal wells depending on the temperature of the injected fluids and receiving formation (Perkins and Gonzalez, 1984).

CO2 Geologic Sequestration

Geologic sequestration of CO2 requires a Class VI UIC permit. The Class VI permitting process includes assessment of potential induced seismicity. Class VI regulations require a detailed review on a site specific basis, consequently Class VI wells were not considered in this report. Some research pertaining to potential seismicity from CO2 geologic sequestration may be applicable to brine disposal.

Commented [A14]: Revised based on OH EPA cmt

Commented [A15]: Changed Oh EPA cmt

Commented [A16]: Revised based on Warpinski cmt

Commented [A17]: SMU and UT BEG:
Mention two examples of true hydrofrac-induced earthquakes. Two other examples are the 1991 California event (Kanamori and Hauksson, BSSA 1992) and the Horn River, British Columbia events (BC Oil and Gas Commission).

Commented [A18]: SMU: A citation or quantification would help demonstrate that the total energy difference for injections accompanying a small geothermal project is much less than the total energy from a large fluid disposal program.
Warpinski comment seems to contradict SMU comment: I do not know why you would suggest that thermal stresses may be of limited applicability to brine disposal wells. We are injecting large volumes of fluid at near-surface temperatures into much hotter rocks; why wouldn't there be significant thermal stresses. You might review a 1984 paper by Perkins and Gonzalez (in SPEJ) for some understanding of its importance.

Anybody have some suggestions how to address this comment?

DIRECTIVE AND WORKING GROUP

Revisions to Class II regulations are outside the scope of this technical report. This report is not a policy or guidance document and does not provide an exhaustive list of specific permitting procedures, but does provide the UIC Director with considerations for minimizing and managing induced seismicity on a site specific basis, using Director discretionary authority.

Commented [A19]: Clarification of intent of report. R9, OH EPA, LBNL,

To address the concern that induced seismicity[11] could interfere with containment of injected fluids and endanger drinking water sources, EPA's Office of Ground Water and Drinking Water of the Drinking Water Protection Division requested the UIC National Technical Workgroup (NTW) develop recommendations for the consideration of UIC regulators (Appendix A). The UIC NTW consists of UIC staff from each EPA Regional office, Headquarters, and six state UIC representatives. The Induced Seismicity Working Group (WG) of the NTW was formed in June 2011 to spearhead development of a report containing recommendations of possible strategies for managing or minimizing significant[12] seismic events associated with induced seismicity in the context of Class II disposal well operations. The WG was comprised of a subset of NTW members and members outside the NTW included for their expertise on the subject matter. A list of the WG members is provided in this report.

REGULATORY AUTHORITIES

This report is intended to describe, for UIC regulators, the current understandings related to induced seismicity within the existing Class II regulatory framework for Class II disposal. Evaluation of induced seismicity is not new to the UIC program. Some UIC wells classes addresses seismicity with specific regulatory requirements.[13] The Class II UIC program does not have regulations specific to seismicity but rather includes discretionary authority that allows additional conditions to be added to the UIC permit on a case-by-case basis as well as additional requirements for construction, corrective action, operation, monitoring, or reporting (including closure of the injection well) as necessary to protect USDWs.[14] In the case studies reviewed for this report, the UIC Directors used this discretionary authority to manage and minimize seismic events.

Commented [A20]: Need to update based on diesel guidance? Diesel guidance classifies production wells Class II EOR. Diesel frac of a Class II disposal well would be stimulation of Class II disposal well.

Potential risks to USDW from seismic events could include loss of disposal well mechanical integrity, impact to various types of existing wells, changes in water level or turbidity of a

[11] Seismic events resulting from human activities are referred to as induced

[12] For the purposes of this report, the Induced Seismicity Working Group considers "significant" seismic events to be those of magnitude to potentially endanger underground sources of drinking water.

[13] 40 CFR §146.62(b)(1) and §146.68(f) for Class I hazardous; §146.82(a)(3)(v) for Class VI geologic sequestration

[14] 40 CFR §144.12(b); 40 CFR §144.52(a)(9); or appropriate section of 40 CFR Part 147 What about 144.52(b)(1)?

USDW, contamination of USDW from a direct communication with the fault inducing seismicity, or contamination from surface sources. The EPA is unaware of any USDW contamination resulting from seismic events related to injection induced seismicity.

Commented [A21]: Added for Satterfield, SMU, and Warpinski cmts

Report Purpose

Our task was not to determine if there was a linkage between disposal and seismicity, but if a linkage was suspected, to identify practical tools the Director may use to minimize and manage injection induced seismicity. The site assessment considerations included were those identified as pertinent by the WG, though other factors may also be appropriate depending on site specific situations. This practical tool also provides operational and monitoring options for managing injection-induced seismicity, and provides a decision model supported by an extensive literature review and four case histories, which considered earthquake history, proximity of disposal well to these events, and disposal well behavior.

Many of the recommendations and reservoir evaluation approaches discussed in this report may be applicable to other well classes. For example, disposal activities also occur in Class I hazardous and non-hazardous wells, various Class V wells, and Class VI wells. The US Department of Energy and International Energy Agency have authored several publications dealing with specific Class V geothermal seismicity issues. The WG reviewed a number of publications as part of the literature survey for this report (Appendix K). Conclusions from some of these reports were applicable to this Class II injection-induced seismicity project and are referenced within the body of the report.

Injection-Induced Seismicity Project Objectives

The WG analyzed existing technical reports, data and other relevant information on case studies, site characterization and reservoir behavior to answer the following questions:

1. What parameters are most relevant to screen for injection-induced seismicity?
2. Which siting, operating, or other technical parameters are collected under current regulations?
3. What measurement tools or databases are available that may screen existing or proposed Class II disposal well sites for possible injection-induced seismic activity?
4. What other information would be useful for enhancing a decision making model?
5. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection-induced seismicity?
6. What lessons have been learned from evaluating case histories?

WORKING GROUP TASKS

The UIC NTW was tasked by UIC management with developing a report including technical recommendations to manage or minimize significant levels of injection-induced seismicity.

The UIC NTW utilized the following approaches to address the objectives:

1. Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Preparation of a decision model
3. Applicability of pressure transient testing and/or pressure monitoring techniques
4. Summary of lessons learned from case studies
5. Recommendations for measurements or monitoring techniques for higher risk areas
6. Applicability of conclusions to other well classes
7. Recommendations for specific areas of research needed

WORKING GROUP APPROACH

The WG adopted the following strategy:

1. Summarize geoscience factors and applications
2. Apply reservoir engineering methods[15]
3. Compile and review historical and current scientific literature including ongoing projects and material associated with upcoming reports on injection-induced seismicity
4. Select and study case examples of Class II brine disposal wells suspected of inducing seismicity and provide a summary of lessons learned for the following areas:
    a. North Texas
    b. Central Arkansas
    c. Braxton County, West Virginia
    d. Youngstown, Ohio

    A study of disposal wells in areas with no seismic activity was not performed
5. ~~Apply reservoir engineering methods[16]~~
6. Develop a Decision Model

Commented [A22]: Comment liked geology 101 but suggested adding seismology 101

Commented [A23]: Added based on Dillon cmt

[15] Reservoir engineering methodologies used in this document adhere to practices and equations commonly presented in petroleum engineering literature

~~[16] Reservoir engineering methodologies used in this document adhere to practices and equations commonly presented in petroleum engineering literature~~

7. Consult with US Geological Survey (USGS) seismologists on the potential for deep stress field measurements and USGS earthquake information as screening tools (See Appendix M)
8. Compare data collected under existing UIC requirements to relevant information needed for assessment of injection-induced seismicity
9. Solicit review by EPA's UIC NTW and subject matter contributors from state agencies, academia, researchers, and industry.

Commented [A24]: Would it be better to make solicit list general, e.g., industry, academia, research, regulatory agencies and then summarize the list that we received comments from. For example, Zoback with Stanford provided no feedback.

These approaches the WG selected are discussed below.

GEOSCIENCE FACTORS RELATED TO INJECTION-INDUCED SEISMICITY

Commented [A25]: Add paragraph about seismology and move this section to an Appendix

Commented [A26]: Nancy, favorably oriented critically stressed fault

Commented [A27]: SMU cmt

The NTW confirmed the following three key components are necessary for significant injection-induced seismicity: (1) critically stressed faults[17], (2) pressure buildup from disposal activities, and (3) a pathway for increased pressure to communicate with the fault. Understanding the geologic characteristics of a site is therefore essential to evaluating the potential for injection-induced seismicity.

Class II disposal well regulations are designed to protect USDWs by ensuring an upper confining layer or layers isolate the disposal zone from the USDW. However, in areas where injection-induced seismicity is a concern, the presence of a lower confining zone may serve to restrict pressure communication with underlying faults. Heterogeneities and a lower confining layer can also substantially affect the size of pressure buildup areas from disposal operations by allowing pressures to dissipate over larger distances or by confining pressures to the injection zone.

Pressure and permeability are critical to understanding the amount of potential pressure buildup and if the pressure influence from the injection site is likely to communicate with a critically stressed fault zone. Though not associated with inducing seismicity, Appendix H provides examples of long distance transmission of pressure buildup from Class II disposal operations, demonstrates the importance of static pressure measurements, and utilizes pressure transient tests in characterizing the disposal interval.

Commented [A28]: Nancy/Phil, should we add something about the favorably oriented critically stressed fault zone? (Based on multiple comments received)

Most of the literature and case examples of possible disposal induced seismicity described in this report, as well as events of natural origin, are related to favorably oriented, critically stressed faults in basement rocks. Basement rocks are those igneous or metamorphic rocks

Commented [A29]: Added based on SMU and ? cmt

Commented [A30]: Should we mention the word crystalline since that was used in the ODNR report?

[17] Critically stressed fault as used in this report denotes a fault that is favorably oriented with the potential to cause a significant earthquake. Fault may refer to a single or a zone of multiple faults and fractures.

that underlie the sedimentary rocks of continents. The contact between basement rocks and overlying younger strata is almost always an erosional surface (Narr et.al, 2006). Basement rocks usually have no effective primary permeability or porosity; however, later weathering or movement can result in fractures and erosional features along the upper surface of basement rocks creating secondary porosity. Faulting of basement rocks can result in fracture porosity and permeability along the fault zone. Some faults occur only in overlying sedimentary rocks. Basement faults may or may not extend into the overlying sedimentary section. Basement faults that are active after deposition of overlying material can extend upward into overlying rock.

Regional evaluations for purposes of assessing induced seismicity potential should consider the geologic history (structural, depositional, geochemical, etc.), earthquake history, and orientation of the current in situ stress field of the fault. In cases where the current in situ stress field is optimally oriented with old or inactive faults that there might be the opportunity for inducing earthquakes along these features. This review should give particular attention to features such as major lineaments, faults (including but not limited to basement faults), fractured formations, and deformation. Tectonic forces acting from plate margins create a stress field at depth across the entire continent.

Commented [A31]: SMU Notes: One point that is not well developed is the orientation of the current in situ stress field with faults. It is worth noting that in cases where the current in situ stress field is optimally oriented with old or inactive faults that there might be the opportunity for inducing earthquakes along these features. I believe that this is mentioned in the USGS appendix but does not seem to have found a place in the body of the report. This association emphasizes the need to characterize both the active and inactive faults in the region as well as their geometry relative to the current in situ stress field.

The history of seismic events in the region and the immediate area will indicate if the area is known to be active. However, seismicity may occur in areas with no previous recorded seismic events. The absence of recorded events may be related to a lack of seismometers, an event trigger, sparse population, and a low natural recurrence rate coupled with a short recording history. Large events (M7) would be recorded in the historical record and possibly in the paleoseismic record. A recent history of tectonic stress or seismic activity in a regional area may be an indicator of critically stressed faults.

Commented [A32]: From SMU comment

Naturally fractured reservoirs are typically described in terms of two rock types, the fracture system and matrix or bulk rock volume. The pressure response from disposal into a naturally fractured reservoir is controlled by the properties of both the fracture and matrix systems and the effectiveness of communication between them. Typical fracture properties might include the number, size and width of the natural fractures, while matrix properties might be characterized by matrix porosity and permeability (Cinco-Ley, 1996; Kamal, 2009). Natural fractures can provide a permeable avenue for fluid flow while the matrix, generally being less permeable, may offer limited availability for pressure dissipation.

Commented [A33]: Moved from Res Eng applications. Use in geosciences discussion, appendix, or delete.

PETROLEUM ENGINEERING APPLICATIONS FOR EVALUATING INDUCED SEISMICITY

Commented [A34]: Moved up to follow Geoscience Factors based on cmt from R5

Petroleum engineering applications have been used for decades in the oil and gas industry to evaluate wells and enhance hydrocarbon production. The induced seismicity literature lacked a multidisciplinary approach inclusive of petroleum engineering techniques. Additionally, a typical Class II disposal permit review would not use many of the petroleum engineering analyses available.

Petroleum engineering methodologies provide practical tools for evaluating the three key components. The key components are (1) fault of concern, (2) pressure buildup from disposal activities, and (3) a pathway for increased pressure to communicate with the fault. Different well and reservoir aspects can be evaluated depending on the methods used. Specifically, Petroleum engineering methods typically address pressure buildup and the pathway present around the disposal well as well as characterizing reservoir behavior during the well's operation. Under limited circumstances, petroleum engineering approaches coupled with geologic and seismologic data may also provide area fault information.

The review process includes information collection typically from the permit application and injection volumes and pressures during operation of the well. The permit application includes the well construction and completion information. Well operations data is acquired through information reported for permit compliance.

Review of operational data can provide a qualitative look at the well behavior. Operational analysis consists of plotting readily available data reported as part of the Class II disposal well permit compliance. These plots include:

- Injection volumes and wellhead pressures
- Bottomhole injection pressure gradient
- Hall Integral and derivative

Plotting injection volumes and pressure and pressure gradients may highlight significant changes in well behavior. For example, a decline in wellhead pressures coupled with an increase in volumes reflects enhanced injectivity. The Hall integral and derivative plot is an operational assessment of injection rates and pressures to look for signs of enhanced injectivity during operations. Details for each plot are included in Appendix C.

In contrast to operational data analysis, supplemental evaluations may be performed. These evaluations quantitatively assess potential pathways and potential reservoir pressure buildup. These evaluations use data or logs that may or may not be routine for Class II disposal permit activities.

- Step rate tests
- Pressure falloff tests
- Production logs
- Static reservoir pressure measurements

Step rate tests are use to determine the formation parting pressure. Analyses are dependent on the amount of pressure data recorded during the test. Pressure falloff can provide the completion condition of the well (wellbore skin) and reservoir flow characteristics. Production logs typically include temperature logs, noise logs, radioactive tracer survey, oxygen activation log, or spinner survey. These are used to evaluate the fluid emplacement at the well. Periodic static pressure measurements provide an assessment of reservoir pressure buildup. More details on supplemental testing and evaluations are included in Appendix C.

Review of Scientific Literature

Literature Sources

Injection-induced seismicity has been documented in many reports from 1968 to2013. The WG compiled and reviewed an extensive reference list included in Appendix K. Injection induced seismicity is a rapidly expanding area of research. This list is not intended to serve as a complete resource list, but does provide several references on topics and case studies used in this report. Inclusion of an article or website in Appendix K does not reflect EPA's agreement with the conclusion of the article.

The USGS Advanced National Seismic System (ANSS) comprehensive catalog (Comcat) is the largest U.S. database of earthquake events. Comcat includes earthquakes from the USGS National Earthquake Information Center (NEIC) and contributing networks. The real-time seismic event report and some of the catalogs include the location accuracy of the event. Catalogs may vary, but are an important consideration for induced seismicity analyses. Earthquake catalogs are discussed more fully in Appendices L and M. USGS, state geologic agencies and universities may also collect and/or host earthquake information on their websites. There may be inconsistencies between databases, such as detection threshold, calculated epicenter, depth, magnitude determination or regional area covered. It should be noted that the expansion or development of regional seismometer networks may measure seismic activity at a lower magnitude threshold than previously recorded, creating the appearance of increased seismicity. Event interpretation is discussed more fully in Appendix K.

THE FUNDAMENTAL THEORY OF INJECTION-INDUCED SEISMICITY

Commented [A35]: Rename if move Mohr-Coulomb to Geoscience Appendix.

The heading doesn't say anything about Mohr-Coulomb, why would that change the heading?

The Mohr-Coulomb failure criterion is the fundamental rock mechanics model describing the fracturing or motion along a fault. The Mohr-Coulomb criterion uses the tectonic stresses on a fault, the frictional resistance of the fault materials, and the fluid pressure within the fault to determine whether or not that fault will slip. In the case of injection-induced seismicity, pore pressure reduces the normal stress across a fault thereby promoting fault movement. Lowering the frictional resistance, means that stresses that were once not high enough to cause failure may now be high enough to cause failure.

Commented [A36]: This paragraph came from USGS.....

Commented [A37]: See Van Arsdale comment

Commented [A38]: Ernie Majer:
Yes, Mohr-Coulomb is a main theory, but rate and state should also be mentioned (Jim Rice's work at Harvard) it may explain some things that M-C theory does not.
A Table of Magnitude versus fault area would be useful (Kanamori and Anderson, 1975 BSSA 65 no 5 1073-1095), have the equations)
Must remember that stress drop is also important!

Commented [A39]: Move to Appendix with Geoscience factors

Or delete???

Fluid injection may relay increased fluid pressures to a fault zone at distance from the injection point. Pressure buildup transference can occur when the disposal zone is in hydraulic communication with the fault zone. Lateral and vertical reservoir pathways to a critically stressed fault could include natural rock fractures, injection-induced fractures, other faults or possibly other mechanisms specific to the disposal zone.

Class II disposal wells may inject over the course of months or years and have a large "pressure footprint" dependent on the injection rates and transmissibility of the reservoir (Lee et al., 2003). In cases where induced seismicity has occurred, the timing of seismicity varies on the character of the flow pathway between a disposal well and fault. After injection has ceased, seismicity may still occur as reservoir pressure buildup diffuses over time or as movement propagates along the fault zone.

Commented [A40]: Ernie Majer cmt

Earthquake magnitude is roughly proportional to the length or area of fault slip (Wells and Coppersmith, 1994).

POSSIBLE CAUSES OF INDUCED SEISMICITY

Seismicity induced by human activities has been extensively documented. Seismic events have been associated with mining, construction of dams and water reservoirs, geologic carbon sequestration, erection of skyscrapers, geothermal energy related injection, oil and gas production activities, and disposal wells. Davis and Frohlich (1993), Nicholson and Wesson (1990; 1992), and Suckale (2009, 2010) studied case histories of potential oil and gas related induced seismicity across the U.S. and Canada. Several waste disposal case studies were investigated including Rocky Mountain Arsenal, Colorado; and two locations in far northeastern Ohio (Ashtabula and Cleveland occurring from 1986 - 2001). Opposing conclusions were drawn on whether the earlier Ohio seismicity was related to injection (Seeber and Armbruster, 1993 and 2004; Gerrish and Nieto, 2003; Nicholson and Wesson, 1990). More recent publications concluded disposal activity induced seismicity in Central Arkansas and Youngstown, Ohio (Horton, 2012; Horton and Ausbrooks, 2011; Holtkamp, et. al., 2013; Kim, 2013; ODNR, 2012).

Commented [A41]: USGS cmt

Disposal activities at the Rocky Mountain Arsenal and the Rangely Field, both located in Colorado, have been associated with inducing seismicity. Operations at both Colorado facilities began prior to UIC regulations being in place. Production from the Rangely Field is still ongoing to date.

Several studies conclude that the Rocky Mountain Arsenal seismicity was caused by injection (Davis and Frohlich, 1993; Nicholson and Wesson, 1990; Nicholson and Wesson, 1992; Suckale, 2009, 2010). At the Rocky Mountain Arsenal, the largest three earthquakes, with magnitudes between 4.5 and 4.8 occurred over one year after injection stopped. In March 1962, injection of waste fluids from chemical manufacturing operations at the Rocky Mountain Arsenal was initiated into a fractured crystalline basement rock beneath the facility. Initial injection exceeded the formation fracture pressure from March 1962 through September 1963 when the surface pump was removed leaving injection under hydrostatic pressure. Pumps were once again used for injection from April 1965 through February 1966 when injection ceased. Seismicity started eight km from the well on April 24, 1962, with magnitudes ranging from 1.5 to 4.4 from 1962 through 1966, and three earthquakes of magnitude ranging from 5.0 to 5.4 in 1967. Subsequent investigations identified a major fault near the well, and showed a direct correlation between increases in bottomhole pressure during injection and the number of earthquakes using Rank Difference Correlation (Healy et al., 1968; Hsieh and Bredehoeft, 1981; Raleigh, 1972).

From 1969 through 1974, the relationship between seismicity and Class II enhanced recovery injection operations at the Rangely field in Colorado were studied (Raleigh, 1972; Raleigh et al., 1976). Reservoir pressures were controlled by varying injection into Class II wells and withdrawal from production wells within the Rangely field to determine the relationship between pressure and induced seismicity. Fourteen seismometers deployed throughout the area recorded events ranging from -0.5 to 3.1 in magnitude, which occurred in clusters in both time and space. Most of these events were below the threshold that is typically felt by humans ~~(magnitude 2.5?)~~[18]. Seismometer data and injection pressure and volume data coupled with modeling confirmed that earthquakes were triggered through an increase in pore pressure. Frictional strength along the fault varied directly with the difference between total normal stress and fluid pressure (Raleigh et al., 1976). Unusual features in this case included measurable response to fluid pressure along one part of the fault; recordable compartmentalization within the reservoir around the fault; and verification that maintaining the reservoir pressure below a calculated threshold stopped the seismicity (Raleigh, 1972;

Commented [A42]: SMU commented we may want to add a depth dependence.
In view of the Cleburne and DFW experience where magnitude 2.0 and below events generated felt reports (as well as news activity) one may want to consider adding a depth dependence to this felt scale. Shallow events and events in the US Northeast have different thresholds.
Warpinski comment: you really should not specify a magnitude threshold for human detection. It depends very strongly on depth, earth conditions, and other parameters.

Commented [A43]: Induced? Or is this a direct quote?

Not a quote

[18] Microseismic and small seismic events may occur but go undetected or unfelt and pose no significant risk to human health or USDWs.

Raleigh et al., 1976). The Rangely field example illustrates how operational changes were used to mitigate induced seismicity.

Commented [A44]: Added based on Warpinski cmt

Numerous earthquakes were induced by Class V disposal operations in Paradox Valley, Colorado (Ake, 2002 and 2005; Block, 2011; and Mahrer, 2005). Seismicity is being managed using intermittent injection periods, injection rate control, and extensive seismic monitoring. Additionally a second Class V disposal well located several miles from the existing well is being evaluated by the U.S. Bureau of Reclamation in response to an expanding area of seismicity. The existing well is required for salinity control of the Delores River and operates above fracture pressure. More information is included in Appendix I.

The “pressure footprint” of an injection well is related to the injection rate, duration of the injection period and transmissibility of the reservoir (Lee et al., 2003). Class II disposal wells typically inject for months or years and generate large “pressure footprints” with no offset production of fluids.

Determinations of Injection-Induced Seismicity

Nicholson and Wesson (1990) stated that induced seismicity determinations rely on three primary characteristics of earthquake activity:

1. Geographic association between the injection zone and the location of the earthquake
2. Exceedance of theoretical friction threshold for fault slippage
3. Disparity between previous natural seismicity and subsequent earthquakes following disposal with elevated pressures

Commented [A45]: Ernie Mejer would add association between injection time and earthquake activity i.e. can you turn on and off seismicity by varying the injection (within a few weeks, maybe longer for larger injections)

But not appropriate in a discussion of someone else’s work who does not include that.

Davis and Frohlich (1993) developed a practical approach for evaluating whether seismic events were induced by injection based on similar characteristics stated by Nicholson and Wesson (1990) e.g., history of previous seismic events, proximity in time and space, and comparison of critical fluid pressures. The Davis and Frohlich approach utilizes a series of fundamental questions to evaluate the likelihood of induced seismicity. These questions are outlined below:

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicenters near wells (within 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressure at hypocenter locations sufficient to encourage seismicity?

Although these approaches are qualitative and do not result in proof of injection-induced seismicity, they may be useful to UIC regulators. Proof of induced seismicity is difficult to achieve, but is not a prerequisite for prudent action to further assess the possibility of induced seismicity by acquiring more data.

Petroleum engineering techniques used in analysis of oil and gas development were not typically considered or used to evaluate reservoir characteristics potentially associated with induced seismicity in the scientific literature reviewed for this report.

CASE STUDY RESULTS

Our task was what practical tools the Director could use to assess the situation or minimize and manage seismicity. Case study efforts were directed toward assessments of typical UIC program compliance data and its usability for characterization of injection well behavior and possible correlation with area seismicity. The case studies were not intended to focus on site problems or program administration issues, but rather to determine if practical assessment tools could be developed.

A total of four geographic areas of suspected injection-induced seismicity were selected by the WG for more detailed evaluation. These case studies were selected from areas where disposal wells were linked with recent seismic events. Initially, North Texas, Central Arkansas, and Braxton County, West Virginia areas were selected. The Youngstown, Ohio, area was included late in the project because a disposal well was the suspected cause of a series of recent seismic events. No cases were evaluated where injection induced seismicity was not suspected.

Initially, the WG identified disposal wells located in the vicinity of recent seismic events in the selected geographic areas. In order to compare well activities to seismic events, a radial area around the well was used to gather seismic data. Historic seismic events for the cases were derived from six different database catalogs. These external databases are discussed in more detail in Appendix L. A radius between five and twelve miles around each case study well was selected based on the spacing density of the existing seismometers and location of the seismicity in the immediate area of the wells. Additionally, there is uncertainty with the depth to the hypocenter.

The specific strategies used by the WG for evaluating the cases included engaging researchers who had studied two of the cases, reviewing available geologic structure maps, acquiring specific injection well data from the four state regulatory agencies and communicating with a well operator. A reservoir engineering analysis based on the collected well data was also performed on each case study well. Additional geoscience background and the results of EPA's

Commented [A46]: No change based on SMU cmt

Commented [A47]: May want to state the intent of the case study review was not to point out problems

Magnitude discussed is in study area or radius around wells.

Commented [A48]: R5 and SMU cmt on distance.

Commented [A49]: Warpinski commented we should mention the uncertainty of the depth.
May add wording in geosciences appendix about excluding too deep of earthquake.

reservoir engineering analysis on these cases are discussed in greater detail in the appendix specific to each case study (Appendices D, E, F, and G).

Each case is discussed below in terms of a background summary relating to the seismic activity and a description of how the case was evaluated by the WG. A summary of the common characteristics and lessons learned from the case studies is included following the case study summaries.

North Texas Area

Several small earthquakes occurred in the central part of the Dallas-Fort Worth metroplex near the Dallas-Fort Worth International Airport (DFW) on October 31, 2008, and near the town of Cleburne on June 2, 2009. Both areas are located in north central Texas, in the eastern portion of the Barnett shale play. Prior to 2008, no earthquakes had been reported within 40 miles of the recent DFW and Cleburne events. Although Barnett shale hydrocarbon production was discovered in Wise County in 1981, extensive drilling into the Barnett shale began in the late 1990s with the advancement of technologies. Disposal wells are the primary management approach to handle the wastewater associated with increased drilling activities. As of January 23, 2013, there are 195 UIC permits for commercial disposal wells in the 24-county area, only 2 of which were permitted in 2012, and not all of which are currently active.[19]

The Railroad Commission of Texas (RRC) standard UIC permit application package incorporated some site data and well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs[20]. Site documentation reviewed by the WG included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and disposal conditions (disposal zone, maximum allowable injection rate and surface pressure). In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. WG review of the annual injection reports indicated that the well operated within the permitted pressure limits. One of the Cleburne area disposal wells was dually permitted as a Class II and Class I disposal well by different regulatory agencies. UIC Class I well requirements include conducting annual falloff tests. These tests provided reservoir characteristics and

[19] RRC of TX website: http://www.rrc.state.tx.us/data/fielddata/barnettshale.pdf

[20] Doug O. Johnson, PE; Railroad Commission of Texas; Presentation to NAS – Committee on Induced Seismicity Potential In Energy Technologies; September 14, 2011; Dallas, TX

pressures for compliance with the Class I well permit and were not required in response to area seismicity. WG reviewed the available falloff tests that confirmed the Ellenburger disposal interval was naturally fractured. More details on this case study are available in Appendix D.

Following the 2008 and 2009 events, the RRC identified active disposal wells in the area for further evaluation as to the possible cause of seismic events due to the wells' proximity to the epicenters of seismic events and the absence of seismicity prior to initiation of disposal. RRC opened a dialogue with the operators of the suspect disposal wells, resulting in the voluntary cessation of two wells, one in the DFW area and one in the Cleburne area, in August 2009 and July 2009 respectively. Since the deactivation of the two wells, the frequency and magnitude of seismic events has substantially decreased.

Commented [A50]: Update after case study is revised and areas defined. Stump says not true in light of new reports – see comment. Frohlich also commented. Not sure if frequency or magnitude or both.

The RRC subsequently reviewed its permit actions for these wells and other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify there were no resulting public safety issues from these events. In follow-up, the RRC consulted with industry representatives, and researchers at the Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M University, and continues to monitor developments and research related to injection-induced seismicity.

Central Arkansas Area

From 2009 through 2011, a series of minor earthquakes occurred in the Fayetteville shale play near the towns of Guy and Greenbrier in Faulkner County, Arkansas. Regionally, the Enola area located approximately nine miles southeast of Greenbrier experienced a swarm of earthquakes starting in 1982[21].

The Arkansas Oil and Gas Commission (AOGC) standard UIC permit application package incorporated site assessment, well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs. Site assessment documentation included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Several of the permit applications contained detailed geologic information, such as a narrative, structure map, type log and additional interpretive data. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and monitored disposal conditions (disposal zone,

[21] Arkansas Geological Survey, 2007, Enola Swarm Area-Faulkner County, Arkansas: GH-EQ-ENOLA-002.

maximum allowable injection rate and surface pressure). In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. For one disposal well closest to the Enola area earthquakes, AOGC also required pressure falloff testing, additional seismic monitoring and intermittent injection during the permitting process. WG review of the annual injection reports indicated that the Enola area well operated within the permitted pressure limits.

In October 2009, three and a half months after injection was initiated, earthquake activity began in the immediate Greenbrier area. To investigate the earthquakes, the AOGC worked with the Arkansas Geological Survey (AGS) and the University of Memphis Center of Earthquake Research and Information (CERI) and additional seismographs were deployed. In December 2010, following increased frequency and higher magnitude earthquakes, AOGC established a moratorium on the drilling of any new Class II disposal wells in an area surrounding and the immediate vicinity of the increased seismic activity. AOGC also required the operators of the seven existing Class II disposal wells operating in the moratorium area to provide bi-hourly injection rates and pressures for a period of six months, through July 2011. During the moratorium period, the AGS and CERI analyzed the injection data and seismic activity to determine if there was a relationship.

In late February 2011, following a series of larger magnitude earthquakes, the operators of three disposal wells nearest to the seismic activity voluntarily terminated well operations prior to the issuance of an AOGC cessation order issued on March 4, 2011. In July 2011, following the conclusion of the moratorium study, AOGC established a revised permanent moratorium area in which no additional Class II disposal wells would be drilled and required four of the original seven disposal wells to be plugged. The revised moratorium area was based on the trend of the Guy-Greenbrier fault, identified as the cause of the seismic activity. The operators of three of the wells voluntarily agreed to plug the subject disposal wells and were consequently not parties to the Commission July 2011 Hearing. Following the July 2011 Commission Hearing, the Commission issued an order to the operator of the fourth disposal well to plug their well. The final moratorium ruling was authorized on February 17, 2012.

Commented [A51]: Rob,
Clarify the Commission vs AOGC.

Unless otherwise approved by the Commission after notice and a hearing, no permit to drill, deepen, re-enter, recomplete or operate a Class II Disposal or Class II Commercial Disposal Well may be granted for any Class II or Class II Commercial Disposal wells in any formation within the following area ("Moratorium Zone") located in Cleburne, Conway, Faulkner, Van Buren, and White counties.

Operators of Class II disposal and commercial disposal wells must submit injection and pressure information on a daily (or more frequent) basis, from monitoring devices approved by AOGC. Additionally, AOGC is studying the feasibility of establishing a permanent seismic array in the Fayetteville shale development area to monitor future disposal well operations, thereby

Commented [A52]: Is this true for all wells, or only wells approved to operate in the moratorium area. This implies the two commercial wells north of moratorium area would have daily data being recorded.

creating an "early warning" system for developing seismic activity, and possibly allowing more time to develop management strategies. More details on this case study are available in Appendix E.

Commented [A53]: Has this decision been finalized?

BRAXTON COUNTY, WEST VIRGINIA

In April 2010, a series of earthquakes ranging in magnitude from 2.2 to 3.4 began in Braxton County, West Virginia. This area had previously experienced a 2.5 magnitude earthquake in 2000 prior to these events. Braxton County is located on the eastern edge of the Marcellus shale play and drilling in this area began in 2006. In March 2009, a nearby Class II disposal well began injecting Marcellus oil and gas production wastewater into the Marcellus formation.

The West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas standard UIC permit application package incorporated site assessment, well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs. The permit application contained detailed geologic information, such as an isopach and structure map. Site assessment documentation included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and disposal conditions (interval, rate, and pressure requested). A step rate test was also included with the permit information. In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. WG review of the annual injection reports indicated that the well operated within the permitted pressure limits. The data reported by the operator indicated that the well did not operate continuously.

In response to the seismic activity, the WVDEP reduced the maximum injection rate in September 2010. No additional earthquakes were recorded in the area since this restriction was enacted until January 2012. In response to the 2012 event, the WVDEP reduced the monthly disposal volume by half the permitted value and is currently researching the geologic structure of the area. The WVDEP and the WG found no conclusive evidence linking the cause of the seismicity to the disposal well.

In February 2012, WVDEP began requiring UIC permit applications to provide detailed geologic information specifically to identify subsurface faults, fractures or potential seismically active features. This includes at a minimum, public or privately available geologic information such as seismic survey lines, well records, published academic reports, government reports or publications, earthquake history, geologic maps, or other like information to access the potential that injection of fluids could lead to activation of fault features and increasing the likelihood of earthquakes. More details on this case study are available in Appendix F.

YOUNGSTOWN, OHIO

Since March 17, 2011, a series of low magnitude earthquakes occurred in Mahoning County in and around Youngstown, Ohio. Based on the reviewed(?) databases, historically, there had been no prior seismicity recorded in the county(?). Commercial disposal operations started in December of 2010 in Mahoning County located on the eastern edge of Ohio. Earthquake activity was located within a mile of the Northstar 1 commercial disposal well.

Commented [A54]: Nancy we need to define area we looked at to make this determination. County?, Region? R8 and OH commented on this sentence.

The Ohio Department of Natural Resources (ODNR) standard UIC permit application package incorporated some site data and well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs. Site documentation reviewed by the WG included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and disposal conditions (interval, rate, and pressure requested). A step rate test was also included with the permit information. In addition, an annual report filed by the operator provides injection volumes and pressure data. WG review of the annual injection reports indicated that the well operated within the permitted pressure limits.

On December 31, 2011, Youngstown experienced a 4.3 magnitude earthquake (ANSS) resulting in the disposal well being immediately shut-in. Prior to the earthquakes recorded in 2011, , the only known deep-seated fault appears to be about 20 miles away from the seismic activity based on a Pennsylvania Geological Survey report. Further details on this case study are available in Appendix G.

Commented [A55]: According to R5, there is now data available from an operator showing a fault near Youngstown. See comment.

According to the *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area* published in March 2012 by the ODNR, data suggests seismicity was related to Class II disposal. The Northstar 1 was drilled 200 feet into the Precambrian basement rock. The ODNR report also suggests that pressure from disposal activities may have communicated with a critically stressed fault located in the Precambrian basement rock. The ODNR will prohibit Class II injection into the Precambrian basement rock and has proposed additional standard UIC permit requirements to facilitate better site assessment and collection of more comprehensive well information. The proposed supplemental permit application documentation will include more geologic data, comprehensive well logs, a plan of action should seismicity occur, a step-rate test, a determination of the initial bottomhole pressure, and a series of operational controls: continuous pressure monitoring system, an automatic shut-off system, and an electronic data recording system for tracking fluids. ODNR is also considering purchasing seismometers to bolster earthquake monitoring capabilities.

COMMON CHARACTERISTICS, OBSERVATIONS, AND LESSONS LEARNED FROM CASE STUDIES

There are common aspects for wells suspected of inducing seismicity from the case studies summarized in this report. Some approaches to minimize and manage injection-induced seismicity can involve a trial and error process, such as disposal rate control. Other aspects and approaches include:

- Initiating dialog with operator can provide early voluntary action from operators, including well shut-in, or acquisition of site data. Initiating dialogue between the operator and UIC regulator resulted in the voluntarily shut in of some suspect disposal wells. For example, an operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep seated fault. (North Texas, Central Arkansas)
- While existing operational data can provide insight into the reservoir behavior of the disposal zone, the quality can be greatly improved by requesting a falloff test or increased recording of operational parameters. For example, fractured flow behavior was confirmed from the falloff test analyses for the Ellenburger disposal zone in a Cleburne area well (North Texas), while increased frequency of permit parameters improved the operational analysis from multiple wells. (Central Arkansas)
- Location of a disposal zone near or into the basement rock may have provided hydraulic access of pressure buildup or disposal fluids to area basement faults. Site data in Central Arkansas and Ohio suggest direct communication with basement rocks or faults communicating with basement rocks. Therefore, regional geologic site assessments may be warranted or existing assessments expanded to evaluate deeper faults, fault trends, and historic seismicity. Published sources may provide regional deep-seated fault information. (all case study areas)
    - Injection into fractured disposal zones overlying basement rock may be vulnerable to injection-induced seismicity. (all case study areas)
- Engaging external seismographic expertise may bring a more accurate location (xyz) of the active fault and stress regime, through reinterpretation or increased seismic monitoring. This is especially true when earthquake event magnitudes increased over time. (Central Arkansas, Ohio and West Virginia) In both North Texas and Central Arkansas, participation by state geological survey or university researchers resulted in expert consultation, installation of additional seismometers, and a clearer understanding of the deep seated active faulting.
- Operational analysis of disposal rates and pressures exhibited enhanced injectivity responses in some wells. Enhanced injectivity could represent injection-induced fracturing, opening or extension of natural~~existing~~ fractures, or higher pressures

Commented [A56]: USGS cmt

Commented [A57]: May clarify if hydraulic or naturally – possibly a footnote and add relevance to induced seismicity (potential pathway).

Commented [A58]: Was log-log included in the report? Does general geologic description of Ellenburger also support naturally fractured flow behavior?

Commented [A59]: Warpinski: you imply that fractured flow behavior is some kind of an indicator of problems. I would hazard a guess that a majority of injection wells exhibit fractured flow behavior which improves their injectivity, but these are not all problem wells. Interpreting falloff tests after long term injection is not necessarily a simple process. What is it that you expect to get out of falloff tests that will provide any insight into the behavior?

Commented [A60]: Warpinski cmt

Commented [A61]: **Nancy, any suggestions?** SMU and Warpinski: The forth lesson learned discusses the importance of increased seismic monitoring to improve earthquake locations. I think this argument can be quantified based on the USGS appendix and that some characteristics numbers including illustrating the large errors typical in regional locations provided by USGS. I think there is an underlying issue that is not discussed here or in the Appendix. Even with close--in stations there will be tradeoffs in the estimate of event depth and the assumed P and S wave velocity model used for the location. As a result, depth will be one of the hardest parameters to estimate even with local instrumentation. There should be some recognition of this fact in the report. Maybe we need to clarify or acknowledge the difficulty in determining the depth/hypocenter. Not sure this is the place to do it though…

allowing fluid flow into lower permeability portions of the formation~~s accepting fluids at higher pressure within the disposal zone~~. (all case study areas)

- Director discretionary authority was used to acquire additional site information, request action from operators, and prohibit disposal operations. Specific examples include:
    - Increased monitoring and reporting requirements for disposal well operators provided additional operational data for reservoir analysis in Central Arkansas.
    - Required one Central Arkansas well to include a seismic monitoring array prior to disposal as an initial permit condition.
    - Plugged or temporarily shut-in suspect disposal wells linked to injection-induced seismicity while investigating or interpreting additional data (all case study areas).
    - Defined a moratorium area in Central Arkansas prohibiting Class II disposal wells in defined high risk area of seismic activity.
    - Decreased allowable injection rates and total monthly volumes in response to seismic activity in West Virginia.
- Operating wells below fracture pressure avoids or minimizes fracture propagation. This may require actual testing, such as a step rate test, to measure the formation parting pressure or conducting an operational analysis for indication of enhanced injectivity.
- Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events. Additional stations installed in the DFW airport area of North Texas and Central Arkansas resulted in reliable identification of active fault locations. In West Virginia, epicenters of recorded events are scattered, due to insufficient stations in proximity to the activity.
- A combination of approaches may be needed to minimize and manage induced seismicity at a given location. (all case study areas)
- The magnitude of the earthquakes may increase over time as observed in some case studies. (Central Arkansas, Ohio and Virginia)

May add conclusion paragraph noting dog bone is needed, one component is insufficient. Must look at all data, one piece may not be enough……

DECISION MODEL

The primary objective of the WG was to develop a practical tool to consider in minimizing and managing injection-induced seismicity in new or existing Class II disposal wells. Based on the historical successful implementation of the UIC program represented by approximately 30,000

Commented [A62]: - Warpinski: "lower permeability formations accepting fluids at higher pressure within the disposal zone" is kind of confusing. Even low permeability zones will have some injectivity at low pressures. As pressures increase, their injectivity will increase, but injectivity of higher permeability zones will increase more unless scaling or fines damage is increasing the skin. Are you suggesting natural fractures may start to open? Fissure opening could happen in any zone.

Commented [A63]: Addresses Warpinski comment - there is discussion about operating wells below fracturing pressure. However, the fracturing pressure is liable to change with time due to increased pore pressure (increased stress) and decreased temperature (decreased stress). Is there any time sequence for measuring the stress? Should it be done at the beginning of injection and then at some prescribed intervals? Certainly you need a baseline if you want it done after some seismicity is detected.

Commented [A64]: Need to edit

disposal wells with less than 10 wells suspected of causing seismic activity[22], the decision model would not be applicable to the majority of existing Class II disposal wells. Use of the decision model is predicated on the UIC Director discretionary authority. The decision model was designed to identify if the three key components of injection-induced seismicity are present. The WG developed a decision model that incorporates a site assessment consideration process addressing the varying reservoir characteristics related to the three key components. The decision model provides the UIC Director flexibility through a combination of site assessment considerations and approaches to identify and address seismicity criteria for both existing and new disposal wells. Site specific information can be applied to determine which considerations listed in the decision model reveal possible issues. No one single question addresses the considerations needed to evaluate a new or existing disposal well. If issues are identified, the decision model discusses operational, monitoring, and management approaches that can be used to address the issues. Regulators may also consider the site assessment considerations for an existing permit should new seismic activity warrant. Federal UIC regulations do not specifically address risk consequences associated with seismicity, but allows Director discretion to ensure protection of USDW.

Commented [A65]: This would include evaluation of risk and consequences mentioned by Satterfield and Mejer.

Commented [A66]: Something to think about adding.

Commented [A67]: Satterfield and Mejer commented on risk not being part of decision model.

Figure 1 includes a diagram of the decision model, and is followed by a discussion relating to the range of considerations for site assessment. Issues identified through the site assessment consideration thought process are then addressed, as needed, by a combination of operational, monitoring, and management approaches. These options were identified by the WG from reservoir engineering methods, literature reviews, analyses of the case studies, and consultations with researchers, operators, and state regulators. A more detailed discussion of the decision model is included in Appendix B.

Site Assessment Considerations

Site assessment considerations identify and evaluate specific site characteristics that may represent potential issues for injection-induced seismicity. The three key components behind injection-induced seismicity are the presence of a critically stressed fault, pressure buildup from disposal activities, and a pathway for the increased pressure to communicate from the disposal well to the fault (Nicholson and Wesson, 1990). Uncertainties about any one of the three components may warrant collection or review of additional data within the site assessment consideration process.

Commented [A68]: Add distance to basement rock

Commented [A69]: Favorably oriented

Site assessment considerations may pertain to permit applications or post approval permit monitoring data. Site assessment considerations may include aspects from both geoscience

[22] NAS report

and petroleum engineering so a multidisciplinary approach is advantageous. The site assessment considerations in the decision model were designed to identify issues relating to any of the three key components. Details about the decision model diagram and its associated site assessment considerations are provided in Appendix B.

Site assessment considerations determined relevant for the decision model were the following:

- Is there a demonstrated history of successful disposal activity?
- Have there been regional area seismic events?
- Is the area geoscience information sufficient to assess the likelihood of faults and seismic events?
- Are the available data sufficient to characterize reservoir pathways?
- Is there adequate information to characterize the potential pressure buildup?
- Is consultation with external geoscience or engineering experts (multi disciplinary approach) warranted?
- Is additional site or regional information warranted?
- **What is the proximity of the injection interval to basement rock?**

Below are three different scenarios. Different site assessment considerations may be applicable to each scenario.

1) An existing disposal well operating in a zone with historical injection and lack of historical seismicity,
2) An existing disposal well in an area not experiencing seismicity, and requests a substantial increase to injection volumes or pressure, or
3) A new disposal well in a disposal zone or area where little or no disposal activity has previously occurred.

Scenario 1) may not warrant further site assessment based on successful historical operations, while scenarios 2) or 3) may warrant additional site characterization consideration, especially if the well was located in a region where the faults are near failure.

Commented [A70]: OH EPA cmt

Commented [A71]: SMU comment: Is this from a local or regional perspective?

Commented [A72]: Confirm mentioned in discussion in App B – OH EPA cmt

Commented [A73]: Based on Warpinski and R9 cmt

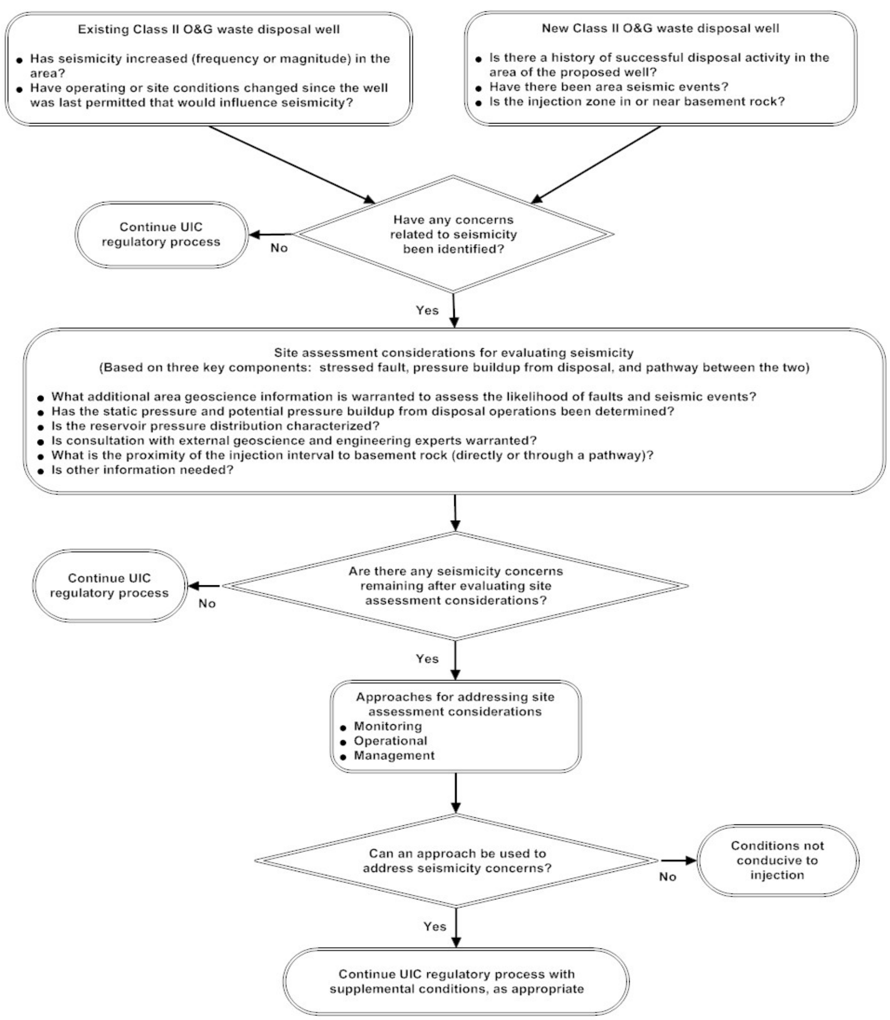
Commented [A74]: Revised for Van Arsdale cmt

FIGURE-1: INJECTION INDUCED SEISMICITY DECISION MODEL

Figure 1

Injection-Induced Seismicity Decision Model for UIC Directors*
(Based on the decision model discussion in Appendix B)

October 18, 2013



* Decision model is founded on Director discretionary authority

Approaches for Addressing Site Assessment Issues

There are a number of approaches available to manage and minimize significant seismic events. These can be broadly categorized as operational, monitoring and management approaches. An operational approach may include, for example, restricting the maximum allowable injection rate or pressure. A monitoring approach may necessitate collection of additional monitoring data, for example, operational pressures, additional seismic monitoring, or well testing. A management approach covers agency, operator and public interaction. The Director determines which, if any, approaches are important depending on site specific considerations. Details about the approaches for addressing issues associated with the site assessment considerations are provided in Appendix B.

Commented [A75]: Add reference to Recommendations section containing detail? Discussion of each is included in Recommendation heading. Would it be appropriate to merge and include here?

Comparison of Data Collected Under Existing Class II Disposal Well Regulations to Relevant Induced Seismicity Data

Class II UIC programs do not specifically require information to assess potential induced seismicity. Director discretionary authority can be used, however, to require data prior to permitting or additional monitoring of an existing well if determined necessary for protection of USDWs. Frequently, well operators collect more comprehensive data with greater frequency than UIC Directors require for reporting. Regulators who invest in frequent communications with operators may have the opportunity to further refine information for an area and minimize the likelihood of induced seismicity. For example, larger oil and gas operators have recommended the relocation of a proposed disposal well located near a large fault identified by internal geoscience information.[23]

Class II disposal well sites are evaluated for the protection of USDWs. Depending on program requirements, regional or area geologic data may be included with the permit applications, illustrating known faulting. Well tests may be included in a permit application for a specific purpose, such as step rate tests to measure fracture pressure or falloff tests to identify flow characteristics, measure static reservoir pressure, or assess well completion condition. An initial bottomhole pressure measurement may be included to determine if the disposal zone is normally pressured, under pressured, or over pressured. The depth of the disposal zone, well construction and completion information, included with the permit application, are also useful data when evaluating induced seismicity.

[23] During the NAS question and answer session of the September 2011 meeting in Dallas, on Induced Seismicity Potential in Energy Technologies, oil and gas operators mentioned they will directly communicate with a smaller operator and suggest relocation of a disposal well or protest a disposal well location during the permit process if internal company information suggests the proposed well is located near a large fault.

A permit application typically includes an evaluation of other well penetrations within the ¼ mile area of review of the disposal well to ensure that the penetration(s) will not serve as vertical conduits or provide a potential for USDW endangerment. Other data to characterize or describe the disposal zone may also be collected depending on the regulatory agency policy. For example, in the West Virginia case study, a step rate test was conducted on the well and submitted with the permit application along with a geologic map in addition to an evaluation of wells within a ¼ mile area of review.

Class II disposal permits are also typically issued with some frequency of injection pressure and rate data reporting requirement as part of permit compliance. There is typically a maximum allowable injection pressure limitation. Review of injection rate and pressure data assist in correlating injection well behavior with area seismicity. For example, pressure responses from disposal activities may change as a result of seismic activity. In the Arkansas case study area, bihourly reporting of operating injection pressures and volumes was required following area seismic activity.

Research Needs

The WG did not exhaust all avenues with respect to research on the value of petroleum engineering approaches. An abundance of research describing seismology and geomechanical behavior in the form of physical rock properties exists although studies that combined petroleum engineering and geoscience approaches could not be found by the WG. The WG recommends future practical research using a multidisciplinary approach and a holistic assessment addressing disposal well and reservoir behavior; geology; and area seismicity. Such an approach would benefit from combined expertise in geology, petroleum engineering, geophysics and seismology, which may not be available through one entity. For example, areas of expertise should include, but may not be limited to structural and stratigraphic geology; rock mechanics; seismology; reservoir characterization; reservoir fluid flow mechanisms; and disposal well construction, completion and performance.

The WG employed Hall plots for the reservoir engineering analysis because regulators may perform the analysis using widely available spreadsheet software; however, other approaches exist, such as the Reciprocal Productivity Index that may be applicable if inverted to injection conditions. WG recommends a practically applied research project focused on assessment of injection well operating data to determine if there is a correlation between operating well behavior and seismicity. One of the key outcomes of the project would be a practical set of methodologies to assess operating data (templates) using injection well operating data acquired for existing UIC permits.

There is also a need for research related to geologic siting criteria for disposal zones for areas with limited or no existing data. The geologic and geophysical study could focus on stratigraphic horizons that could serve as disposal zones in these areas, the nature of subsurface stresses in basement rocks of these areas, and a more detailed regional geological assessment of basement faults. If sufficient earthquake catalog data are available, additional research to devise a statistical approach to relate Class II disposal wells operating parameters with induced seismicity would be useful.

REPORT FINDINGS AND OBSERVATIONS

Commented [A76]: Warpinski and Dillon both commented Many of these common factors could also occur in wells that have not caused induced seismic events. This statement is correct so we need further clarification that need a complete dog bone, not just a piece.

Three key components behind injection-induced seismicity are the presence of a critically stressed fault, pressure buildup from disposal activities, and a pathway for the increased pressure to communicate from the disposal well to the fault. Successful disposal occurs in areas with one or two characteristics (favorably oriented critically stressed fault, pressure buildup from disposal operations and pathways for pressure buildup from disposal activities to reach the fault) are present, but not all three. Understanding the geologic characteristics of a site is therefore essential to evaluating the potential for injection-induced seismicity.

Unconventional resources and new technologies have resulted in the need for disposal wells in areas with few or no existing wells. Uncertainties in site geology and reservoir characteristics may exist in areas with limited to no historic drilling or exploration operations.

An absence of historical seismic events in the vicinity of a disposal well does not provide assurance that induced seismicity will not occur; however, this absence may be a supportive indicator of induced seismicity if events occur following activation of an injection well. Proof of induced seismicity is difficult to achieve, but is not a prerequisite for prudent action to further assess the possibility of induced seismicity by acquiring more data. Some events started at a lower magnitude and showed a general increase over time, such as in the Arkansas and Ohio case studies.

In Arkansas and Ohio, the magnitudes of early events were low, and showed a general increase over time to a point of being significant. Data from the West Virginia case suggest reducing injection rate and volume requirements reversed the increasing magnitude/frequency trend. This action may have prevented the ultimate closure of the disposal well.

There are common factors related to wells suspected of inducing seismicity, both from the literature and recent examples:

- The magnitude of the earthquakes in some cases showed general increases over time.
- Deep disposal wells were in direct communication or suspected to be in hydraulic communication with basement rocks and critically stressed faults as in the Arkansas and Ohio case study examples.
- Disposal commonly occurred into disposal zones with naturally fractured reservoir characteristics as in the Arkansas and North Texas case study examples.
- Operational analysis of injection rates and pressures exhibited enhanced injectivity responses, possibly representative of injection-induced fracturing, extension of existing fractures, or lower permeability formations accepting fluids at higher pressure within the disposal zone. Enhanced injectivity was observed in all the case study areas.

Commented [A77]: May need to note many disposal zones are naturally fractured, but need rest of dog bone to be an issue. See sentence below bullets - Warpinski cmt

As observed in the case studies, no single factor by itself leads to induced seismicity, but a combination of conditions is necessary to induce seismicity.

The accuracy of measurements of seismic events is dependent on the quantity and location of seismometers (Daley et al., 2010; Eager et al., 2006; Grasso and Wittlinger, 1990). A regional view of seismic history may give an indication of subsurface stresses in an area that has no local seismic history. Subsequent reviews of seismic surveys in two of the cases (DFW North Texas, and Arkansas) identified nearby deep faults as the source of the seismic activity. In the Arkansas case study area, there is a history of clustered seismic events approximately 9 miles to the southeast.

In the case studies, the UIC Directors took action through discretionary authority to manage and minimize seismic events. The WG also found no indication that the injection wells associated with the case study areas injected outside of the operational boundaries or designated injection zones established by the permit parameters or endangered a USDW.

Basic petroleum reservoir engineering practices coupled with geoscience information can provide a better understanding of reservoir and fault characteristics (Lee et al., 2003; Kamal, 2009). The reservoir engineering analysis of operational data identified anomalies in some case study wells, which could have warranted additional site assessment or monitoring. The WG noted that published research was generally narrowly directed and lacked a multidisciplinary approach of how disposal wells and induced seismicity interrelate.

There are a variety of human activities, which are documented in the literature, that have induced seismicity (Davis and Frohlich, 1993; Nicholson and Wesson, 1990; Suckale, 2009, 2010; Coplin and Galloway, 2007). Seismicity requires the presence of a critically stressed fault (Ahmad and Smith, 1988; Majer et al., 2011; Nicholson and Wesson, 1990; Nicholson and Wesson, 1992). Significant[12] seismic events induced by HF have not been documented in the

Commented [A78]: Favorably oriented?

literature reviewed for this report. HF generally induces microseismic magnitude (<1.0) events (Maxwell, 2011; Phillips et al., 2002; Warpinski, 2009) although HF into a critically stressed fault has produced seismicity up to magnitude 2.8 (de Pater and Baisch, 2011; Holland, 2011).

Commented [A79]: Favorably oriented?

In naturally fractured reservoirs, assessment of primary storage capacity (fractures and/or matrix) and its impact on pressure buildup is critical in determining if the zone is a viable disposal zone. The areal extent of pressure buildup from disposal activities is controlled by injection rates and reservoir characteristics of the injection interval (Kamal, 2009; Lee et al., 2003). Measurement of the initial bottomhole pressure prior to disposal provides the Director a baseline for assessing the pressure impact from disposal activities. Depleted reservoirs may have a larger differential of pressure buildup prior to inducing seismicity. Pressure buildup associated with Class II brine disposal wells can be transmitted over extended distances from the wellbore.

Operational and monitoring practices for managing and minimizing injection-induced seismicity that were used or proposed in the scientific literature and case examples in this report include:

- Start at lower injection rates and increase gradually while monitoring seismic activity to determine appropriate injection rate with acceptable seismicity, which will likely be a trial and error process
- Increased monitoring frequency of injection parameters such as formation pressure and rates
- Intermittent injection operations to allow time for pressure dissipation, with the amount of shut-in time needed being site specific
- Use of multiple injection wells separated by some distance to more widely dissipate subsurface pressures
- Operate wells below fracture pressure to prevent or minimize fracture propagation that may require actual testing, such as a step rate test, to measure the formation parting pressure or conducting an operational analysis for indication of enhanced injectivity
- Installation of seismic monitoring instruments in areas of concern to allow more accurate location determination and increased sensitivity for seismic event magnitude
- Conduct falloff test to characterize the flow regime of the disposal zone
- Acquire periodic reservoir pressure measurements to assess the pressure buildup in the reservoir

RECOMMENDATIONS TO MINIMIZE OR MANAGE INJECTION-INDUCED SEISMICITY

The WG found no single recommendation addresses all the complexities related to managing or minimizing injection-induced seismicity. Recommendations included in this report were derived from a combination of WG expertise, case studies, consultations with outside experts, and data from literature reviews. These can be divided into three technical categories (site assessment, well operational, and monitoring) and a management component. The first step in the induced seismicity evaluation process is to conduct a site assessment. Based on the site assessment, further operational and monitoring approaches may be warranted.

Site Assessment

- Use the decision model site assessment considerations for determining if the well site may need additional requirements to ensure protection of USDWs. These include:
  - Assess past disposal history for correlation with area seismicity.
  - Evaluate regional and local seismicity to identify local principal stress directions.
  - Evaluate regional and local area geoscience information to assess the likelihood of activating faults and causing seismic events.
  - Review the available data to characterize reservoir pathways which could allow pressure communication from disposal activities to a critically stressed fault.
  - Assess the pressure buildup potential by evaluating the storage capacity of disposal formations prior to use, especially those with low porosity and permeability.
  - Consult with external geoscience or engineering experts as needed to acquire or evaluate additional site information.
  - Consider collecting additional site assessment information in areas with no previous disposal activity and limited geoscience data or reservoir characterization prior to authorizing disposal.
- Request more geoscience and reservoir engineering information, as needed to minimize injection-induced seismicity, to reliably assess reservoir behavior during injection. Many reservoir engineering considerations for site characterization are not part of the typical permit application process.
- Determine the primary storage capacity (fractures and/or matrix) of naturally fractured reservoirs to assess the impact on pressure buildup and determine if the zone is a viable disposal zone.
- Measure the initial bottomhole pressure prior to disposal to determine if the disposal zone is normally or depleted. Depleted reservoirs may have a larger differential of pressure buildup from Class II disposal injection prior to inducing seismicity.
- Conduct geologic evaluations for purposes of assessing induced seismicity potential and consider the tectonic and geologic history with an expanded area of evaluation for earthquake history and fault trends.

Well Operations

- Conduct a reservoir engineering analysis of operational data on wells in areas where seismicity has occurred. Basic reservoir engineering practices coupled with geoscience information can provide a characterization of the flow behavior in the injection zone, quantify reservoir conditions and delineate fault characteristics.
- Conduct pressure transient testing in disposal wells suspected of causing seismic events to obtain information about injection zone characteristics near the well.
- Modify injection well permit operational parameters as needed to minimize or manage seismicity issues. For example:
  - Reduced injection rates: This approach is likely a trial and error process, starting at lower rates and increasing gradually.
  - Inject intermittently to allow time for pressure dissipation, with the amount of shut-in time needed being site specific.
  - Separate multiple injection wells by a larger distance for pressure distribution since pressure buildup effects in the subsurface are additive.
  - Contingency measures in the event seismicity occurs.
- Operate wells below fracture pressure to maintain the integrity of the disposal zone and confining layers. This may require actual testing, such as a step rate test, to measure the formation parting pressure or conducting an operational analysis for indication of enhanced injectivity.

Commented [A80]: Make sure we aren't contradicting NAS report.
SMU comment: NAS report stated, "No capability to predict how reducing volumes, rates, and pressures will affect seismicity once started"

Monitoring

- Require additional seismometers as needed for increased accuracy of seismic information. The accurate measurement of seismic events depends on the quantity and location of seismometers.
- Increase monitoring frequency of injection parameters, such as formation pressure and rates, to increase the accuracy of analysis.
- Increase monitoring of fluid specific gravities in commercial disposal wells with disposal fluids of variable density since the density impacts the bottomhole pressure in the well.
- If mechanical integrity is a concern, annular pressure tests and production logging can be performed.

Management

Commented [A81]: Seismic threshold

Several proactive practices were identified for managing or minimizing injection-induced seismicity.

- Take earlier action to minimize the possibility of injection-induced seismicity rather than requiring substantial proof.
- Engage the operators early in the process, especially in areas that are determined to be vulnerable to injection-induced seismicity.
- Provide training for UIC Directors on new reservoir operational analysis techniques to understand the spreadsheet parameters.
- Employ a multidisciplinary team for practical research to address the links between disposal well and reservoir behavior; geology; and area seismicity.
- Engage external multidisciplinary experts from other agencies or institutions. For example, engineers may engage geophysicists to interpret or refine data from seismic events for accuracy and stress direction.
- Develop public education programs to explain some of the complexities of injection-induced seismicity.

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GLOSSARY OF ACRONYMS AND TERMS

ACRONYMS

AAPG	American Association of Petroleum Geologists
AGS	Arkansas Geological Survey
ANSS	USGS Advanced National Seismic System
AOGC	Arkansas Oil and Gas Commission
BHP	Bottomhole Pressure
CERI	Center for Earthquake Research and Information
EPA	US Environmental Protection Agency
HF	Hydraulic Fracturing
GIA	Geothermal Implementing Agreement
IEA	International Energy Agency
MMbls	Million barrels
NCEER	Central and Eastern United States, CERI Earthquake database
NEIC	National Earthquake Information Center, US Geological Survey
NTW	National Technical Workgroup
PDE	Preliminary Determination Earthquake, NEIC Earthquake database
RRC	Railroad Commission of Texas
SMU	Southern Methodist University
SPE	Society of Petroleum Engineers
SRA	Eastern, Central & Mountain States NEIC Earthquake database
UIC	Underground Injection Control
USDW	Underground Sources of Drinking Water
USGS	US Geological Survey
USHIS	Significant US quakes, NEIC Earthquake database
WG	Injection-induced Seismicity Working Group
WVDEP	West Virginia Department of Environmental Protection Office of Oil and Gas

TERMS

Catalog aka earthquake catalog from USGS online Earthquake Search of the NEIC PDE catalog of earthquakes. http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

Class II injection wells inject fluids (1) which are brought to the surface in connection with conventional oil or natural gas production and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection, (2) for enhanced recovery of oil or natural gas; and (3) for storage of hydrocarbons which are liquid at standard temperature and pressure (40 CFR 146.5(b)).

Critically stressed fault for this report denotes a fault with the potential to cause a significant earthquake.

Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth (USGS). Earthquakes resulting from human activities will be called induced earthquakes in this report.

Epicenter is the point on the earth's surface vertically above the hypocenter (or focus) point in the crust where a seismic rupture begins. NEIC coordinates are given in the WGS84 reference frame. The position uncertainly of the hypocenter location varies from about 100 m horizontally and 300 m vertically for the best located events, those in the middle of densely spaced seismograph networks; to tens of kilometers for ~~global~~ events in ~~many parts of the world, including~~ large parts of the U.S.

Isopach is a contour map illustrating the variations of thickness of defined stratum.

Magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on the measurement of the maximum motion recorded by a seismograph or the energy released. Generally, damage is reported for magnitudes above 5[24]. Magnitude will refer to the numbers reported by USGS or the NEIC, not separated between moment, body wave, or surface wave magnitudes.

Magnitude[25]	Earthquake Effects
2.5 or less	Usually not felt, but can be recorded by seismograph.
2.5 to 5.4	Often felt, but only causes minor damage.
5.5 to 6.0	Slight damage to buildings and other structures.
6.1 to 6.9	May cause a lot of damage in very populated areas.
7.0 to 7.9	Major earthquake. Serious damage.
8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.

[24] Building damage was reported following 2011 earthquakes near Trinidad, Colorado (5.3); near Greenbrier, Arkansas (4.7), and the Soultz France project (2.9).
[25] (Michigan Tech, 2011)

Commented [A82]: Term stressed fault. Is that an accepted term with a citation in the literature or is this a first use here?

Commented [A83]: Add something about favorably oriented critically stressed faults to address SMU comments

Commented [A84]: Van Arsdale comment: "stress changes". I suggest replacing stress changes with release of elastic strain energy.

Commented [A85]: Revised to address SMU comment: Position uncertainty. While a later appendix points out that 'many parts of the world' includes large parts of the US, this may be worth pointing out here as well.

Commented [A86]: Added to footnote.
SMU comment: Damage. Damage is relative and dependent on construction practices, regional and local geology, earthquake depth, and geologic and cultural hazards. The included table may lead one to consider that any earthquake under M5 could be ignored. From a public perspective this is not the case, since the Soultz France project was ended due to possible damage to structures from a M 2.9 earthquake

Microseismicity has no formal definition, but generally is an earthquake with a magnitude less than 2. (*The Severity of an Earthquake*, USGS website: http://earthquake.usgs.gov/learn/topics/richter.php)

Step rate test consists of a series of increasing injection rates as a series of rate steps and estimates the pressure necessary to fracture the formation.

Significant seismic events for use in this report are of a magnitude to potentially endanger underground sources of drinking water.

Tectonic is the rock structure and external forms resulting from the deformation of the earth's crust. (Dictionary of Geological Terms, 1976)

CITATIONS

Ahmad, M. U., and Smith, J. A., 1988, Earthquakes, injection wells, and the Perry Nuclear Power Plant, Cleveland, Ohio: Geology, v. 16, no. 8, p. 739-742.

Ake, J. et al., 2002, What's shaking in bedrock? Paradox Valley deep-well injection program: Outcrop, v. 51, no. 4.

Ake, J. et al., 2005, Deep-injection and closely monitored induced seismicity at Paradox Valley, Colorado: Bulletin Seismological Society, v. 95, no. 2, p. 664-683.

Ausbrooks, S.M. and Doerr, E., 2007, Enola Swarm Area of Faulkner County, Arkansas: GH-EQ-ENOLA-002, Arkansas Geological Survey, 1 sheet.

Block, L., 2011, Paradox Valley deep disposal well and induced seismicity, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas, Bureau of Reclamation, US Department of the Interior.

Cinco-Ley, H., 1996, Well Test Analysis for Naturally Fractured Reservoirs: Journal of Petroleum Technology, 48(1): p. 51-54; SPE-31162-MS.

Coplin, L. S., and Galloway, D., 2007, in Houston-Galveston, Texas Managing coastal subsidence, http://pubs.usgs.gov/circ/circ1182/pdf/07Houston.pdf.

Daley, T. M., Haught, R., Peterson, J. E., Boyle, K., Beyer, J. H., and Hutchings, L. R., 2010, Seismicity characterization and monitoring at WESTCARB's proposed Montezuma Hills geologic sequestration site: Lawrence Berkeley National Laboratory.

Das, I., and Zoback, M. D., 2011, Long period long duration seismic events during hydraulic stimulation of a shale gas reservoir, Article #40761, Search and Discovery, American Association of Petroleum Geologists/Datapages, Inc.

Davis, S. D., and Frohlich, C., 1993, Did (or will) fluid injection cause earthquakes? Criteria for a rational assessment: Seismological Research Letters, v. 64, no. 3-4.

de Pater, C. J., and Baisch, S., 2011, Geomechanical study of Bowland Shale seismicity synthesis report: Cuadrilla Resources.

Eager, K. C., Pavlis, G. L., and Hamburger, M. W., 2006, Evidence of possible induced seismicity in the Wabash Valley Seismic Zone from improved microearthquake locations: Bulletin of the Seismological Society of America, v. 96, no. 5, p. 1718-1728.

Gerrish, H., and Nieto, A., 2003, Review of injection reservoir information in relation to earthquakes in Ashtabula, Ohio, 2nd International Symposium, Underground Injection Science and Technology: Symposium Abstracts: Berkeley, California, Lawrence Berkeley National Laboratory, p. 156.

Gidley, J. L., Holditch, S. A., Neirode, D. E., and Veatch, J., R. W., eds., 1990, Recent advances in hydraulic fracturing, SPE Monograph Series Volume 12, Society of Petroleum Engineers, p. 464.

Grasso, J.-R., and Wittlinger, G., 1990, Ten years of seismic monitoring over a gas field: Bulletin of the Seismological Society of America, v. 80, no. 2, p. 450-473.

Hall, H.N., 1963, How to analyze waterflood injection well performance: World Oil, October 1963, p 128-130.

Healy, J. H., Aubrey, W. W., Griggs, D. T., and Raleigh, C. B., 1968, Denver earthquakes: Science, v. 161, no. 3848, p. 1301-1310.

Holland, A., 2011, Examination of possibly induced seismicity from hydraulic fracturing in the Eola Field, Garvin County, Oklahoma, Oklahoma Geological Survey, Open-File Report OF1-2011.

Hsieh, P. A., and Bredehoeft, J. D., 1981, Reservoir Analysis of the Denver earthquakes: A case of induced seismicity: Journal of Geophysical Research, v. 86, no. B2, p. 903-920.

Hunt, S. P., and Morelli, C. P., 2006, Cooper Basin HDR seismic hazard evaluation: Predictive modelling of local stress changes due to HFR geothermal energy operations in South Australia, *in* Adelaide, U. o., ed., South Australian Department of Primary Industries and Resources, Government of South Australia.

Izgec, B., and Kabir, C. S., 2009, Real-time performance analysis of water-injection wells: SPE Reservoir Evaluation & Engineering, v. 12, no. 1, p. 116-123.

Jarrell, P. M., and Stein, M. H., 1991, Maximizing injection rates in wells recently converted to injection using Hearn and Hall plots, Document ID 21724-MS, Society of Petroleum Engineers Production Operations Symposium: Oklahoma City, Oklahoma, Society of Petroleum Engineers.

Kamal, M. M., 2009, Transient well testing: Monograph 23: Richardson, Society of Petroleum Engineers, p. 850.

Lee, J., Rollin, J. B., and Spivey, J. P., 2003, Pressure transient testing, SPE Textbook Series, Society of Petroleum Engineers.

Mahrer, K. et al., 2005, Injecting brine and inducing seismicity at the world's deepest injection well, Paradox Valley, Southwest Colorado: Developments in Water Science, v. 52, p. 361-375.

Majer, E. L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B., and Asanuma, H., 2007, Induced seismicity associated with enhanced geothermal systems: Geothermics, v. 36, p. 185-222.

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., and Wong, I., 2011, Protocol for addressing induced seismicity associated with enhanced geothermal systems, Accessed November 22, 2011 (http://www1.eere.energy.gov/geothermal/pdfs/egs-is-protocol-final-draft-20110531.pdf), Last updated unknown.

Maxwell, S., 2011, Imaging hydraulic fractures using induced microseismicity, *in* National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies, Dallas, Texas.

Michigan Tech, 2011, Earthquake Magnitude Scale, Michigan Technological University, Accessed December 15, 2011 (http://www.geo.mtu.edu/UPSeis/magnitude.html), Last updated unknown.

Narr, W., Schechter, D., and Thompson, L., 2006, Naturally Fractured Reservoir Characterization, An Interdisciplinary Approach to Topics in Petroleum Engineering and Geosciences, Society of Petroleum Engineers, 112 p.

Nicholson, C., and Wesson, R. L., 1990, Earthquake hazard associated with deep well injection, *in* Bulletin, U. G. S., ed.

Nicholson, C., and Wesson, R. L., 1992, Triggered earthquakes and deep well activities: Pure and Applied Geophysics, v. 139, no. 3-4, p. 561-568.

ODNR, 2012, Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area: Ohio Department of Natural Resources, 24 p. plus figures. http://www.ohiodnr.com/home_page/NewsReleases/tabid/18276/EntryId/2711/Ohios-New-Rules-for-Brine-Disposal-Among-Nations-Toughest.aspx

Perkins, T. K. and J. A. Gonzalez, 1984, Changes in Earth Stresses Around a Wellbore Caused by Radially Symmetrical Pressure and Temperature Gradients: , SPEJ April 1984, pp 129-140.

Phillips, W. S., Rutledge, J. T., House, L. S., and Fehler, M. C., 2002, Induced microearthquake patterns in hydrocarbon and geothermal reservoirs: Six case studies: Pure and Applied Geophysics, v. 159, no. 1-3, p. 345-369.

Raleigh, C. B., 1972, Earthquakes and fluid injection: Experiment in earthquake control at Rangely, Colorado, AAPG Memoir 18: AAPG Special Volumes, American Association of Petroleum Geologists.

Raleigh, C. B., Healy, J. H., and Bredehoeft, J. D., 1976, An experiment in earthquake control at Rangely, Colorado: Science, v. 191, no. 4233, p. 1230-1237.

Stein, S., and Wysession, M., 2003, Introduction to Seismology, Earthquakes, and Earth Structure: Malden, Massachusetts, Blackwell Publishing, 498 p.

Suckale, J., 2009, Induced seismicity in hydrocarbon fields: Advances in Geophysics, Academic Press, p. 55-106.

Suckale, J., 2010, Moderate-to-large seismicity induced by hydrocarbon production: The Leading Edge, v. 29, no. 3, p. 310-319.

US Geological Survey, 1995, The October 17, 1989, Loma Prieta, California, Earthquake - Selected Photographs, US Geological Survey, Accessed December 15, 2011 (http://pubs.usgs.gov/dds/dds-29/), Last updated July 2, 2009.

Warpinski, N., 2009, Microseismic monitoring: Inside and out: Journal of Petroleum Technology, v. 61, no. 11, p. 80-85.

Warpinski, N., Du, J., and Zimmer, U., 2012, Measurements of Hydraulic-Fracture-Induced Seismicity in Gas Shales: SPE 151597 presented at the Society of Petroleum Engineers Hydraulic Fracturing Technology Conference, The Woodlands, Texas, 6-8 February.

Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

APPENDIX A: UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC #2011-3

UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC: #2011- 3

Technical Recommendations to Address the Risk of Class II Disposal Induced Seismicity

Background

Recent reports of injection-induced seismicity have served as a reminder that the UIC Program can and should implement requirements to protect against significant seismic events that could ultimately result in USDW contamination. The UIC Program's Class I hazardous and Class VI siting provisions require rigorous evaluations for seismicity risks. The other well classes, in contrast, allow the UIC Director the flexibility to decide if and when such evaluations are needed. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to inform and enhance strategies for avoiding significant seismicity events related to Class II disposal wells.

Project Objectives

The UIC NTW will analyze existing technical reports, data and other relevant information on case studies, site characterization and reservoir behavior to answer the following questions:

1. What parameters are most relevant to screen for injection induced seismicity? Which siting, operating, or other technical parameters are collected under current regulations? (Geologic siting criteria, locations and depths of area pressure sources and sinks, injection rates and pressures, cumulative injection or withdrawals of an area, evaluation of fracture pressure, stresses or Poisson's ratio, etc.)
2. What measurement tools or databases are available that may screen existing or proposed Class II disposal well sites for possible injection induced seismic activity? What other information would be useful for enhancing a decision making model? (Flow chart incorporating seismicity/hazard database resources, reservoir testing methods, area faulting, measuring or recording devices, reservoir pressure transient models, seismic models, other screening tools, etc)
3. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection induced seismicity?
4. What lessons have been learned from evaluating case histories?
    a. Did reviews of injection rate and pressure data sets reveal any concerns?
    b. Were any pressure transient tests conducted?
    c. How were the seismicity events attributed to Class II disposal activities?
    d. What levels of site characterization information were available?
    e. Which UIC regulations have regulators used to address the situation?
    f. Were there areas of concern identified that existing UIC regulations did not address?
    g. Any other lessons learned?

Output
The end-product of this analysis should be a report containing technical recommendations for avoiding significant levels of injection induced seismicity that EPA can share with UIC Directors. The UIC NTW will produce a report that includes the following elements:

1. Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Prepare a decision making model – conceptual flow chart
    a. Provide strategies for preventing or addressing significant induced seismicity
    b. Identify readily available applicable databases or other information
    c. Develop site characterization check list
    d. Explore applicability of pressure transient testing and/or pressure monitoring techniques
3. Summary of lessons learned from case studies
4. Recommended measurement or monitoring techniques for higher risk areas
5. Applicability of conclusions to other well classes
6. Define if specific areas of research are needed

Milestones

- July 2011 – Authorization from UIC managers for UIC NTW to proceed with injection induced seismic project proposal. Assemble UIC NTW project team and assign tasks to project members. Collect and distribute, to UIC NTW project team, information from published studies, peer-reviewed articles, and State and Federal UIC programs.
- August 2011 – Create project sub-teams. Collect and evaluate information from case histories. Review compilation of information and develop technical recommendations for addressing risks of significant injection induced seismicity. Create project teams.
- September 2011 - Consolidate input from project sub-teams
- October 2011 – Prepare and present preliminary technical recommendations and report to UIC NTW membership. Finalize technical recommendations and report with input from UIC NTW membership.
- November 2011 – Submit report for presentation to UIC management
- December 2011 – Finalize report and post to public accessible UIC NTW website

Project Focus Group
Phil Dellinger (R6; Lead); Leslie Cronkhite (HQ; HQ-Lead); Jill Dean (HQ); Bob Smith (HQ); David Albright (R9); Sarah Roberts (R8); Tom Tomastik (Ohio Department of Natural Resources); Steve Platt (R3); Dave Rectenwald (R3), Susie McKenzie (R6), Brian Graves (R6), Ken Johnson (R6), Nancy Dorsey (R6), state representatives associated with case histories.

Target Delivery Date: December 2011

Headquarters Approval

Ann Codrington 7/20/11

Ann Codrington, Acting Director
Drinking Water Protection Division
Office of Ground Water and Drinking Water

Date

SPECIFIC GUIDANCE TO WORKGROUP: (space unlimited)

APPENDIX B: DECISION MODEL

INTRODUCTION

A key objective of this project was to develop a practical tool for UIC regulators to use in the evaluation of potential injection-induced seismicity or to manage and minimize suspected injection induced seismicity. As a result, a decision model was developed, consisting of a recommended thought process for Directors to consider based on site specific data from the Class II disposal well area in question. Options for additional actions are included in this model.

The absence of recorded historical seismic events in the vicinity of a proposed Class II injection well does not mean there were not historic low-level seismic events below detection level. With the increased deployment of modern and more accurate portable seismic units or seismic arrays, many previously undetected low-level seismic events are now being documented in some areas of the United States. The increased deployment of these seismic instruments further enhances the ability to detect low-level seismic events, whether naturally occurring or induced. However, the occurrence of measurable seismicity after the initiation of disposal in areas with little or no historic seismicity supports the possibility of induced seismicity.

Class II disposal activities have existed for decades without inducing significant seismicity. This decision model may not be applicable to areas with historically demonstrated successful disposal activities. Because of complex variations in geology and reservoir characteristics across the country, it is neither practical nor appropriate to provide a detailed step by step decision model. Instead, the use of Director discretionary authority will determine the applicability of this decision model to Class II disposal well activities and the need to address site specific conditions. The model presented in this report summarizes the various considerations and approaches identified by the Working Group (WG) from reservoir engineering methods, geosciences considerations, literature review, analysis of the case studies, consultations with researchers, operators, and state regulators, and feedback from subject matter experts. The decision model is included as Figure 1 in the report.

Areas for Review

Throughout the decision model discussion and Figure 1, the “area” referenced is a geographic area with the extent being determined by the Director based on usage, whether as a screening tool or a focused site specific basis. The geographic area can also vary based on geologic setting and the available seismic monitoring network. Therefore designating the term “area” with a specific areal extent was not practical for this report.

Options for a screening seismicity review include looking at the overall seismicity history of a broad area, state wide or by geologic province. A simple method is to use both a statewide historical seismicity map prepared by either USGS or another seismicity reporting service; and the Quaternary Fold and Fault Map created by a USGS consortium. Appendix _ contains links and a more detailed discussion of these maps. This screening area could then be further subdivided by the level of seismic activity or quiescence.

In seismically active areas, the focused area of interest may center on the disposal well and related geologic structure of interest. For example, a more detailed, localized review may be recommended by the Director to further evaluate the potential for local geologic structure that could impact the injection well operations. In the determination of the size of the focused search area, the Director should consider geology and the density of seismometers, which impacts the accuracy of the recorded seismic events in both the lateral and vertical directions. Generally, because of reduced seismometer spacing, accuracy of hypocenter locations outside of active seismic zones is on average six miles (Appendix _, Task 1). Vertical accuracy varies significantly depending on seismic processing assumptions and seismometer density, but the error range is typically 1 to _miles (1-10 km). The accuracy of seismic events can be further refined by the deployment of portable units around the disposal well.

Quiescent areas are less likely to be of concern for injection induced seismicity. For seismically active areas, the Director may decide to continue through the decision model process and address potential induced events through other means.

Existing versus New Class II Disposal Well

Existing Class II Oil and Gas Waste Disposal Well

Two primary reasons the Director may find the decision model useful for existing wells are: 1) increased seismicity or 2) change in operating condition of a well located in areas susceptible to seismic events. On a case by case basis, the Director may elect to continue further into the decision model by utilizing site assessment considerations to address potential concern for or minimize and manage existing induced seismicity. During operation of the disposal well, should seismicity concerns arise, the Director may revisit the decision model.

Increased seismicity can be determined from various means such as media reporting, available seismic databases, or USGS Earthquake Notification Service by area and magnitude. Appendix _ lists available databases. A change in relevant operating or site conditions since the well was last permitted may prompt further review by the Director. Relevant parameters should relate to the key components for inducing seismicity (pressure buildup, reservoir pathway, or fault of concern).

New Class II Oil and Gas Waste Disposal Well

For new disposal well applications, the Director may consider if there is history of successful disposal activity in the proposed well area. Successful disposal activity would be years of historical disposal in the same geographic area and disposal zone. New wells located in such an area would not be of concern. Whereas, a new disposal well located in an area with no previous disposal activity in the proposed zone may require additional analysis. Uncertainties in reservoir characterization may exist in new areas with few or no existing wells, possibly justifying the need for additional site characterization information and analysis. Additionally, the location of the disposal zone relative to basement rock may be a consideration on a site by site basis. Again, Director knowledge of the area and historic disposal activity may determine the need for further site consideration process.

Have Any Concerns Related to Seismicity Been Identified?

If Director does not identify any injection induced seismicity concerns, the well evaluation would exit the decision model and continue through the normal UIC regulatory process; otherwise, a continuation through the model for further site assessment considerations may be warranted. For a disposal well suspected of initiating seismic activity during its operational life, the Director determines the appropriateness of advancing the well further through the decision model. The Director may also determine a level of seismicity relevant for further evaluation.

Site Assessment Considerations for Evaluating Seismicity

Once the Director has identified potential concerns related to induced seismicity, additional site assessment considerations may be justified. With few exceptions, injection-induced seismicity occurs in response to increased pore pressure from injection, transmitted through a pathway, to a critically stressed fault plane (Nicholson and Wesson, 1992). Therefore, the WG identified site specific assessment considerations for evaluating significant seismicity. These considerations may not all be applicable and are not listed in any order of importance. The Director determines which considerations may be applicable for an existing or proposed Class II disposal well based on site specific information. Ultimately, through discretionary authority, the Director may require additional site assessment information or monitoring for the protection of USDWs.

Site assessment considerations focus on identifying if any of the three key components of injection-induced seismicity (the presence of a fault of concern, pressure buildup from disposal activities, and a pathway for the increased pressure to communicate from the disposal well to the fault) are present. The considerations included in the decision model are discussed individually below, along with the positive and negative aspects for each.

- WHAT ADDITIONAL AREA GEOSCIENCE INFORMATION IS WARRANTED TO ASSESS THE LIKELIHOOD OF FAULTS AND SEISMIC EVENTS?

With few exceptions, injection-induced earthquakes occur in response to increased pore pressure from injection, transmitted through a pathway to a critically stressed fault plane in an optimal orientation. Understanding the area geology through available geosciences information may clarify two of these induced seismicity components: the nature of the pathway transmitting the pore pressure response and identification of faults of concern subject to the pressure response. The lateral continuity and heterogeneity of the disposal zone influence both the pressure buildup from disposal operations and the distribution pathway. The effectiveness of overlying and underlying confining zones may influence the dispersion of pressure in all directions.

Accurate fault assessment, as part of the overall site characterization, is a critical aspect of managing injection-induced seismicity (Nicholson and Wesson, 1990). Subsurface faults exist throughout most of the country; however, the presence of a fault itself may not be a concern. If a site is in an area with a history of seismic activity, critically stressed faults are likely present in the region. Consideration should be given to the possibility of deep seated faulting, as reported with the Rocky Mountain Arsenal (Hsieh and Bredehoeft, 1981) and Central Arkansas induced events (Ausbrooks, 2011a, 2011b, 2011c, 2011d; Horton and Ausbrooks, 2011).

There are a number of possible options for determining the presence or absence of faulting around a proposed or existing disposal well, including a review of published literature, state geological agency reports, commercial structure maps or evaluating seismic surveys[26]. While the latter are the most definitive, they are also the most expensive, time consuming to acquire, and may require access to land that cannot be readily obtained. Well operators may have exploration seismic surveys to enhance fault analysis for the site characterization. For example, active faults in Arkansas and the Dallas-Fort Worth, Texas (DFW) area were identified first from seismic activity, and then verified on the operator's interpreted 3D seismic surveys, (Chesapeake Energy, personal communication, meeting September 16, 2011). If seismic surveys are available, a reanalysis may help identify any deep seated faults, and if present, the extent of the fault or associated fractures, although some faults, such as those that are near-vertical strike-slip, may be missed. Correlations of geophysical logs or review of geologic cross-sections may indicate missing or faulted out rock sections. If a fault is present, information on the origin, displacement, and vertical extent of the fault may be a consideration. Geophysical logs may also identify the rock characteristic of the disposal zone and the reservoir pathways the pressure from disposal operations may encounter. If site specific geosciences information is limited or insufficient and regional studies indicate faults or subsurface stress in the broader area, additional information may be needed to evaluate the likelihood of inducing seismicity.

Geologic site characterization information on flow characteristics, fracture networks and stress fields may be available from: 1) regional and local geologic studies, or 2) information from geophysical logs, core analysis, and hydraulic fracturing results. Any published articles discussing the basin, reservoir rock or structural history of the area, may indicate if faulting, fracturing, or directional flow is present.

- HAS THE STATIC PRESSURE AND POTENTIAL PRESSURE BUILDUP FROM DISPOSAL OPERATIONS BEEN DETERMINED?

Reservoir pressure buildup, a key component of induced seismicity, is influenced by reservoir flow behavior, disposal rate, and hydraulic characteristics of the disposal zone. To perform conventional reservoir pressure buildup calculations, knowledge of disposal zone hydraulic characteristics is required. Disposal zone hydraulic characteristics include static reservoir pressure, permeability, effective net thickness, porosity, fluid viscosity, and system

[26] Seismic survey lines are typically proprietary, but may be obtained commercially or viewed by special arrangement. If provided, the data may be submitted as confidential business information.

compressibility. Details about these characteristics are generally determined from some combination of fluid level measurements, pressure transient testing results, logging and completion data, and fluid and rock property correlations. The static pressure provides a starting point for determining the pressure buildup during disposal activities. Once these values are obtained, the pressure buildup calculations can then be performed to access the magnitude of pressure increases throughout the disposal reservoir.

Typically an infinite acting homogeneous reservoir with radial flow is assumed for the pressure buildup calculation. In many Class II disposal applications, limited reservoir property measurements are available and actual pressure buildup calculations are done using assumed or accepted area formation characteristic values. Reservoir falloff tests can provide clarity as to whether the homogeneous reservoir behavior assumption is valid or pressure buildup projections should be calculated using a different set of fluid flow behavior assumptions. A static bottomhole pressure measurement, typically obtained at the end of a falloff test may also provide an assessment of reservoir pressure increase around the injection well, offering insight into the magnitude of pressure buildup to which the area fault may have been subjected.

Naturally fractured disposal formations involving induced seismicity may require more complex pressure buildup prediction methods to account for non-radial reservoir behavior. For example, several cases of suspected injection-induced earthquakes in the literature appear to be characterized by injection zones located within fractured formations (Belayneh et al, 2007; Healy et al, 1968; Horton and Ausbrooks, 2011).

- IS THE RESERVOIR PRESSURE DISTRIBUTION PATHWAY CHARACTERIZED?

The potential pathway or the ability of the reservoir to transmit pressure to a critically stressed fault is best characterized by a combination of geosciences and petroleum engineering information. Geologic information can help characterize the nature and continuity of the disposal zone. For example, a geologic isopach map or cross-section, may define the lateral continuity of the disposal zone and the area potentially impacted by the pressure response from disposal operations. Evaluation of the confining capability of formations overlying and underlying the disposal zone may indicate the potential for pressure dispersal outside the disposal zone. A type log from the disposal well or area offset well may illustrate if confining layers are present. Other useful aspects for consideration include the number of formations and thickness of permeable strata included within the disposal zone. Heterogeneities in the receiving formations will impact the pathway for pressure distribution away from the disposal well. This level of detailed information, while useful, is not typically required for Class II disposal well operations and therefore may not be available in all situations.

Review of daily drilling reports and open-hole geophysical logs may suggest characteristics of the disposal zone and overlying confining zones, helping to describe the reservoir pathway. For example, borehole washouts or elongated boreholes observed on a caliper log may suggest a higher stressed or fractured zone. Heavier mud weights used while drilling may suggest the presence of higher pressure zones. Core data are not typically acquired during the drilling of Class II disposal wells, but if available, could show natural fractures (open or sealed), karstic rock or fault gouging if present. Open-hole geophysical logs, such as a fracture finder log, multi-arm dipmeter, borehole televiewer, or variable-density log may also assist in identifying fractured zones.

Production logging data in an existing well may supplement geologic data by providing additional insight about out of interval fluid movement and vertical pressure dispersal. Production logs such as radioactive tracer surveys, temperature logs, noise logs, flowmeters (e.g., spinner surveys) and oxygen activation logs can show where fluid exits the wellbore and allow estimates of fluid volumes being emplaced into the intervals identified. Wellbore fill at the base of a well may reduce the interval thickness, alter the injection profile, and increase the pressure buildup during disposal operations. For example, wellbore fill may cover a large portion of the disposal zone in a well with a short perforated interval; resulting in a greater pressure buildup within the thinner interval receiving fluid. Production logs can also indicate if fluid is channeling upward or downward behind the casing to other intervals for potential hydraulic impact and show intervals impacted by cumulative long term injection.

Reservoir engineering approaches, such as a reservoir falloff test, can also provide clues about the pressure transmission pathway, by indicating whether the injection zone is behaving in a linear flow (possibly fractured) or homogeneous radial flow (non-fractured) manner. Falloff testing is not a requirement for Class II wells, but has been used as a lower cost alternative in some Class II operations to characterize the disposal reservoir flow parameters, reservoir pressure buildup, and well completion condition. Falloff testing is associated with the petroleum reservoir engineering approach which is discussed in further detail in Appendix C.

- IS CONSULTATION WITH EXTERNAL GEOSCIENCE AND ENGINEERING EXPERTS WARRANTED?

Site assessment considerations may require multidisciplinary evaluations, necessitating consultations with geophysicists, geologist, and petroleum engineers. Consulting with seismologists and geophysicists at either state or federal geological surveys can provide additional information and may be necessary in situations based on existing site specific conditions. For example, in the Arkansas case study, the UIC Program coordinated with researchers from Memphis University and Arkansas Geological Survey to successfully acquire critical information on ongoing low level seismic activity. Data from this effort formed the basis for a disposal well moratorium in the area of disposal induced seismicity.

Seismic history for any area in the U.S. is readily available on the USGS website (see Appendix _) and/or state geological agencies at no cost. However, if there is sufficient seismic information, seismologists can refine the event locations and depths. This could identify fault locations.

Geologists can provide insight on reservoir geologic data and identify the presence of faults or potential for faulting. Reservoir analysis by petroleum engineers may evaluate the completion condition of the disposal well, provide estimate of pressure buildup and characterize distribution efficiency of the pressure away from the disposal well. Other expertise may be available through academia, other agencies, or consultants.

Commented [A87]: No. pressure down a fault is efficient

- WHAT IS THE PROXIMITY OF THE INJECTION INTERVAL TO BASEMENT ROCK?

Most of the literature and case examples of alleged disposal induced seismicity described are related to favorably oriented, critically stressed faults in basement rocks. Therefore depth of the disposal zone to the basement rock or a flow pathway from the disposal zone to the basement rock may be a consideration. A comprehensive study of disposal in basement rock was not part of this study. Cases of successful disposal in basement rock may exist.

A lower confining layer between the disposal zone and basement rock may restrict pressure communication with underlying faults thereby minimizing the conditions for induced seismicity. Critically stressed fault as used in this report denotes a fault that is favorably oriented with the potential to cause a significant earthquake. Fault may refer to a single or a zone of multiple faults and fractures.

- IS OTHER INFORMATION NEEDED?

Based on review of the available site characterization information, the Director may require additional information as needed based on the unique site specific circumstances.

ARE THERE ANY SEISMICITY CONCERNS REMAINING AFTER SITE ASSESSMENT?

If Director does not identify any injection induced seismicity concerns following a more detailed site assessment, the well would exit the decision model and continue through the normal UIC regulatory process. When an injection induced seismicity concern is identified the Director may determine an approach to address the concern.

APPROACHES TO ADDRESS SITE ASSESSMENT CONSIDERATION

The WG identified operational, monitoring, and management approaches to potentially address any significant seismicity concerns identified after evaluating site assessment considerations. Some of the approaches could overlap in classification.

Selecting the appropriate approaches depends on a number of factors. Key factors for addressing site assessment concerns are knowledge of the area and timing of seismic events relative to disposal activities. Characterizing the flow behavior in the injection zone, quantifying reservoir conditions and delineating fault characteristics is best accomplished using a multidisciplinary team. The Director may elect to set up contingency measures in the event seismicity occurs or increases.

Operational Approaches

Operational approaches beyond shutting in the well may be applicable, though some may involve modification to permit conditions or additional reservoir testing. Some of these approaches are discussed in the following paragraphs.

Reducing injection rates or implementing intermittent injection may decrease reservoir pressure buildup and allow time for pressure dissipation. Determining the reduction in pressure buildup needed to manage or minimize seismicity is likely a trial and error process. The resulting maximum allowable disposal rate or amount of shut-in time needed to remain below a determined reservoir pressure would be site specific. There would be no direct cost to implement, though the reduced disposal volume could impact facility operations and wastewater management.

Confirming site specific fracture pressure through testing defines a limiting operating pressure value. Operating below the fracture pressure maintains the integrity of the disposal zone and confining layers. Operating a well above fracture pressure could create new pathways by initiating or extending a fracture. Determining the site specific fracture pressure may require actual testing, such as a step rate test, to measure the actual formation parting pressure in lieu of a calculated fracture gradient. Additional cost would be associated with conducting a step rate test.

Conducting pressure transient tests in disposal wells suspected of causing seismic events may reveal the injection zone characteristics near the well, flow regimes that control the distribution of reservoir pressure, and completion condition of the well. A series of pressure transient tests may provide an indication that the reservoir characteristics and pathway remain consistent throughout the life of the well. Pressure transient testing would require some additional cost to the operator as well as specialized expertise to design and review the data.

Profiling where fluids are exiting the wellbore by running production logs, such as a flowmeter (spinner survey), radioactive tracer survey, or temperature log may be another useful testing technique for evaluating fluid emplacement. The thickness of the interval receiving fluid can impact the amount of pressure buildup in the reservoir. The location of fluid emplacement could provide insight on the reservoir pathway. Additional costs would be incurred by the operator to run the logs.

Verifying mechanical integrity following a seismic event may include performing tests to evaluate the well and bottomhole cement. Annulus pressure tests can evaluate the integrity of the tubing, packer and production casing. A temperature log, noise log, or radioactive tracer survey can confirm the location of fluid emplacement and verify no out of zone channeling of fluids.

Conducting a reservoir engineering analysis of available operational data (rate and pressure) on wells in areas where seismicity has occurred may provide a characterization of the flow behavior, such as enhanced injectivity, in the injection zone. Operational analysis can also quantify reservoir conditions and delineate fault characteristics. Operational analysis uses UIC compliance data so there is no additional cost to acquire data.

The specific gravity of the wastewater impacts the hydrostatic pressure component of the bottomhole pressure. Regularly measuring fluid specific gravities, especially in commercial disposal wells with variable disposal fluid density, allows conversion of surface pressures to bottomhole operating pressures with no additional costs to acquire data.

Pressure buildup effects in a formation are additive so separating multiple injection wells by a larger distance may reduce the amount of pressure buildup, but again the results would be site specific depending on the quality and size of the disposal zone and number of disposal wells completed in the same formation. Higher costs would likely be associated with drilling multiple wells and transferring wastewater to the additional wells.

Monitoring Approaches

Monitoring approaches focus on reservoir pressure and well condition during disposal operations along with levels of area seismic activity. In many cases, monitoring approaches would be conducted in conjunction with the other approaches.

Requiring more frequent operational data collection to assess site specific situations relevant to induced seismicity may be useful. The increased monitoring frequency adds improved data quality and quantity for use with operational approach analysis methods. More accurate data may require electronic measuring equipment to record and store data which may add cost. The frequency of data collection can influence the accuracy of the analysis. For example, in the Arkansas case study, bi-hourly monitoring of injection pressure and volume yielded more data for analysis than the monthly data typically reported.

Monitoring static reservoir pressure provides an indication of the pressure buildup in the formation over time. Depending on the site specific conditions, static pressure can likely be obtained using a surface or downhole pressure gauge or fluid level measurement. A static reservoir pressure is easy and inexpensive to obtain, however it requires the well be shut-in for a period of time prior to the measurement.

Monitoring for seismic events using a pre-existing seismic network may provide an early warning of seismic activity, if suitably configured and continuously evaluated. The monitoring program could use the existing USGS seismic monitoring network or include seismometers proactively installed prior to the injection operation. Tracking earthquake trends (magnitude and event frequency) for events in an area of possible induced seismicity can reveal possible increases in seismicity even before the events become significant. For example, in the Arkansas, Ohio, and West Virginia case studies, an upward trend in the magnitude of associated events is apparent.

Additional seismometers would result in more accurate locations of seismic events and greater sensitivity to detect smaller events. The USGS recommends configuring a monitoring network capable of detecting a minimum of M=2 event. For example, in Arkansas, additional monitoring stations were deployed. The additional monitoring stations provided increased accuracy and resolution level of seismic events leading to identification of a previously unknown basement fault. Additional seismic monitoring stations and data analysis requires additional costs as well as geophysical expertise to process and review.

MANAGEMENT APPROACHES

Management approaches address agency, operator and public interaction. As discussed below, these approaches provide proactive practices for managing or minimizing injection-induced seismicity.

Undertaking earlier action rather than requiring substantial proof prior to action by the Director to minimize and manage injection-induced seismicity is a prudent approach for a number of reasons. Early proactive action, such as reducing operating conditions to decrease pressure build-up may avoid escalation of event magnitudes. Early discussions with surrounding operators may allow access to additional data, for example 3-D seismic data. For example, in the DFW area, communication between the Director and operator resulted in the voluntary shut-in of a suspect disposal well. Early action may also increase public confidence in the regulatory agency.

Contacting external multidisciplinary experts from other agencies or institutions to address site assessment concerns may result in improved quality of response to seismicity concerns. For example, geophysicists may be able to interpret the active fault from the seismic events along with stress directions; while geologists provide an overall picture of the setting; and engineers evaluate the well responses in conjunction with comments from the others. An initial cooperative effort may have minimal cost.

Providing technical training for UIC Directors, specific to reservoir engineering evaluations or geosciences techniques could benefit preparedness of the program and expand options for minimizing and managing seismicity. At a minimum, it would raise awareness of the advantages and disadvantages of the various techniques and disciplines. Some costs may be associated with the training.

Utilizing a multidisciplinary team for practical research for links between disposal well and reservoir behavior; geology; and area seismicity allows all complex aspects of seismicity to be reviewed. It may be possible to utilize in-house personal from other sectors to aid in the effort.

Developing public education programs to explain some of the complexities of injection-induced seismicity may have some value.

Establishing a contingency plan, e.g., based on a seismic threshold, can assure that specific expedited response actions by the injection well operator occur in response to surrounding area seismic events. For example, contingency conditions could be as simple as immediately working with the permitting agency to evaluate the situation. Using existing seismic monitoring and reporting databases is inexpensive, but limited data accuracy may require additional expense to supplement the existing network.

Can an Approach be Used to Address Seismicity Concerns?

The site assessment considerations are intended to guide the Director in selecting which operational, monitoring, and management approaches are appropriate to address induced seismicity issues. If the Director does not identify a suitable approach to address seismicity concerns, conditions may not be suitable to disposal operations at that location. If monitoring, operational or management approaches provide the required level of protection, the Director may condition the permit accordingly or use discretionary authority to require the desired approaches needed without revoking the permit.

Citations

Ausbrooks, S. M., 2011a, Exhibit 23: Geologic overview of north-central Arkansas and the Enola and Greenbrier earthquake swarm areas, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011b, Exhibit 24: Overview of the E. W. Moore Estate No. 1 well (Deep Six SWD) and small aperture seismic array, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011c, Exhibit 25: Clarita Operating, LLC, Wayne Edgmon SWD data, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011d, Exhibit 30: Docket 063-2008-01, initial Deep Six permit hearing, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Belayneh, M. et al., 2007, Implications of fracture swarms in the Chalk of SE England on the tectonic history of the basin and their impact on fluid flow in high-porosity, low-permeability rocks, *in* Ries, A. C., Butler, R. W. H., and Graham, R. H., ed., Deformation of the Continental Crust: The Legacy of Mike Coward: Special Publications: London, The Geological Society of London, p. 499-517.

Healy, J. H., Aubrey, W. W., Griggs, D. T., and Raleigh, C. B., 1968, Denver earthquakes: Science, v. 161, no. 3848, p. 1301-1310.

Horton, S., and Ausbrooks, S., 2011, Earthquakes in central Arkansas triggered by fluid injection at Class 2 UIC wells, National Academy of Science Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas.

Hsieh, P. A., and Bredehoeft, J. D., 1981, Reservoir Analysis of the Denver earthquakes: A case of induced seismicity: Journal of Geophysical Research, v. 86, no. B2, p. 903-920.

Nicholson, C., and Wesson, R. L., 1990, Earthquake hazard associated with deep well injection, *in* Bulletin, U. G. S., ed.

Nicholson, C., and Wesson, R. L., 1992, Triggered earthquakes and deep well activities: Pure and Applied Geophysics, v. 139, no. 3-4, p. 561-568.

APPENDIX C: PETROLEUM ENGINEERING CONSIDERATIONS

Petroleum engineering approaches offer many ways of assessing disposal well behavior and reservoir properties that may contribute to injection-induced seismicity. This appendix provides more details on the petroleum engineering analyses and methods used for this project and analyses of the case studies. Other petroleum engineering methods or applications may also be useful to operators and UIC Director in evaluating injection-induced seismicity. Collectively, petroleum engineering techniques may assist in a site-appropriate evaluation of the three key components of potential injection-induced seismicity.

Another aspect of the project included application of petroleum engineering techniques. Petroleum engineering methodologies provide core tools for evaluating the three key components of injection-induced seismicity as part of the site assessment process. A petroleum engineering based site assessment may provide important details by quantifying reservoir transmissibility, and by characterizing the flow pathways that together impact the amount and distribution of pressure buildup from disposal operations. Characterizing flow pathways helps determine if the pressure buildup is being dispersed radially or in a preferential direction from the disposal well. An analysis of available operational data may not provide conclusive proof of induced seismicity, but may suggest if additional reservoir testing or discussions with geologists are warranted.

What are petroleum engineering considerations?

Site assessment considerations in the decision model focus on three key components for the occurrence of injection-induced seismicity: a fault of concern, disposal interval pressure buildup and a reservoir flow pathway to transmit the pressure buildup from the disposal well to the fault. Petroleum engineering methods address pressure buildup and the pathway present around the disposal well as well as characterizing reservoir behavior during the well's operation. Under limited circumstances, petroleum engineering approaches coupled with geologic and seismologic data may also provide area fault information. These methodologies can provide both quantitative and qualitative descriptions of the disposal wellbore and reservoir conditions.

Petroleum engineering methods encompass various well aspects including well construction, well completion, well operations, and reservoir characterization to evaluate and optimize well performance. In this report, these fundamental petroleum engineering methods were applied to evaluate disposal wells in the four case study areas using available data. The WG assessment process examined injection well operational and reservoir behavior in regard to seismic event activity.

Petroleum Engineering Information Collection

Information collection focuses on disposal wellbore details and how these parameters might contribute to injection-induced seismicity. Well construction and completion conditions, the well's injection profile (where the injected waste is emplaced), and injection rate determine bottomhole injection pressure and conditions that may impact the zonal isolation of the injected fluids. Applications of these aspects are detailed below.

UIC Class II disposal permits typically include disposal well construction and completion data such as the well completion date, casing and tubular dimensions and depths, cementing records, total well depth, packer depth and type, waste density, completion interval(s) and type (e.g., open-hole, screen and gravel pack, or perforations), and initial pressure prior to disposal. Detailed knowledge of the well layout is necessary for assessing the isolation of the disposal zone through cemented casing, geological confining layers, location of the disposal zone relative to basement rock, and if the disposal zone includes multiple intervals or is focused on a single interval.

Knowledge of the waste density and wellbore tubular dimensions coupled with the injection rate enables calculation of an operating bottomhole pressure by accounting for the hydrostatic pressure of the brine column and friction pressure loss of the tubing. This calculation is particularly useful for converting surface pressure injection history to bottomhole conditions.

The operational bottomhole pressure gradient trend can be compared against the estimated or measured fracture gradient for the disposal zone to assess if injection-induced fracturing is a concern. Static bottomhole pressures can be estimated from the static fluid level or surface pressure and brine density.

Cased hole and production logs can also provide useful information on the wellbore condition to assess injection operation conditions. Production logging data may supplement geologic data by providing additional insight about out of interval fluid movement and vertical pressure dispersal. Cased hole logs such as a cement bond log can identify properly or poorly cemented portions of the injection casing. Production logs (radioactive tracer surveys, flowmeters, temperature, oxygen activation, and noise logs) provide information about injection profiles, zonal isolation, and upward and downward fluid channeling. The wellbore injection profile shows where fluid is going into the formation, which in turn controls the reservoir pressure buildup response. Annular pressure tests and production logging can also confirm well mechanical integrity if this is a concern following area seismic activity.

Temperature logs typically require the well be shut-in for 36 to 48 hours prior to running the log so the temperature differential between the injected fluid and reservoir temperature can be effectively measured. Radioactive tracer tests use slug chases or velocity shots to evaluate the injection profile in the well. The radioactive ejector tool has limited capacity and may require multiple trips in and out of the well to reload the ejector tool when profiling large disposal zones. Flowmeters, such as a spinner survey, are typically less effective in large diameter casing or open-hole intervals. Production logs are routinely used for Class I hazardous waste injection wells, but are not typically required for Class II disposal wells. Several of the case study wells had long vertical open-hole completions, but no assessment of the injection profile. In the Ohio case study, a production log was conducted to assess the portion of the disposal zone receiving fluid.

UIC operational compliance case history data generally included monthly injection volumes with maximum and/or average surface injection pressures. Using this data along with the well construction and completion information, the WG assessed well construction conditions and calculated operating bottomhole injection pressures for each case study well. The calculated bottomhole operating pressures were then used in the reservoir engineering approach analyses.

Available Class II Data

The most common data available for Class II disposal wells are injection rates/volumes and injection tubing pressures. Such data are routinely reported as part of both EPA direct implementation and state UIC Class II program requirements. Bottomhole pressures (BHP), more suitable for evaluating reservoir conditions, are not as readily available. The timeframe for reporting injection volumes and pressures varies between regulatory agencies and depends on site circumstances. Although less common, pressure transient test data are occasionally available.

The following data types may be available for Class II disposal wells:

Common UIC monitoring data reported:

- Injection rates or volumes
- Surface tubing pressures

Common data submitted in UIC permit applications:

- Well construction
    - Tubular (tubing/casing) dimensions and depth
    - Cementing information
    - Completion type and interval
- Reservoir information
    - Gross and net injection zone thickness
    - Porosity
    - Name and description of disposal zone and overlying confining zones
    - Bottomhole temperature
    - Initial static BHP
- Reservoir and injection fluids
    - Specific gravity
    - Fluid constituent analysis

Though less common, these pressure test measurements may also be available:

- Falloff/injectivity test: reservoir characterization and well completion condition
- Step rate test: fracture gradient
- Static pressures: initial pressure and pressure change during well operations

Petroleum Engineering Analysis of Operational Data

The WG focused on petroleum engineering analysis of any available data sets for correlation with reservoir behavior and geologic environment. The petroleum engineering approach couples reservoir rock and fluid properties with time, pressure, and injection rate data from well operations to describe and predict reservoir behavior. Analysis of disposal well operating data and well testing, such as pressure transient tests, can provide details about the injection interval reservoir pathway and the completion condition of the well. Operating injection rates and pressures are typically collected as part of the permitting compliance activity and consequently more readily available than pressure transient tests. Completion conditions reflect conditions at or near the wellbore while reservoir characteristics describe the injection interval away from the well. For example, a well that has been fracture stimulated displays a different response than an unfractured well.

Reservoir characterization assesses the injection formation flow patterns, the formation's capacity to transfer pressure responses, and the completion condition of a disposal well. Identifying anomalous reservoir behavior through such analyses and then correlating the results with geoscience data may suggest relationships between injection well pressure response and induced seismic activity. The petroleum engineering approach was incorporated into the case study analyses.

Operational Data Plots and Analyses:

Both operating data and pressure transient data shown on appropriate plots represent "pictures" of mathematical responses that can be fit to reservoir models which qualitatively and, in some cases, quantitatively characterize well completion and performance conditions, reservoir flow geometry, and, in limited cases, reservoir geology. Graphs of typically reported injection volume and operational pressures reflect reservoir behavior over time. Longer periods of operational data (typically in months or years) results in a deeper, though less refined look into the reservoir than a shorter timeframe pressure transient test.

Graphical format for the reservoir engineering analytical plots varies, ranging from tandem linear axes to dual log axes depending on the type of analysis performed. The graphs may display certain patterns or quantitative values which inform the reservoir analyst as to what type of reservoir flow characteristics are present or identifies changes in reservoir behavior over time. Reservoir characteristics identify the type of disposal zone reservoir pathway present and indicate its tendency to dissipate pressure buildup, either radially or in a preferential direction. Hence, the data can be used to "describe" the reservoir pathway.

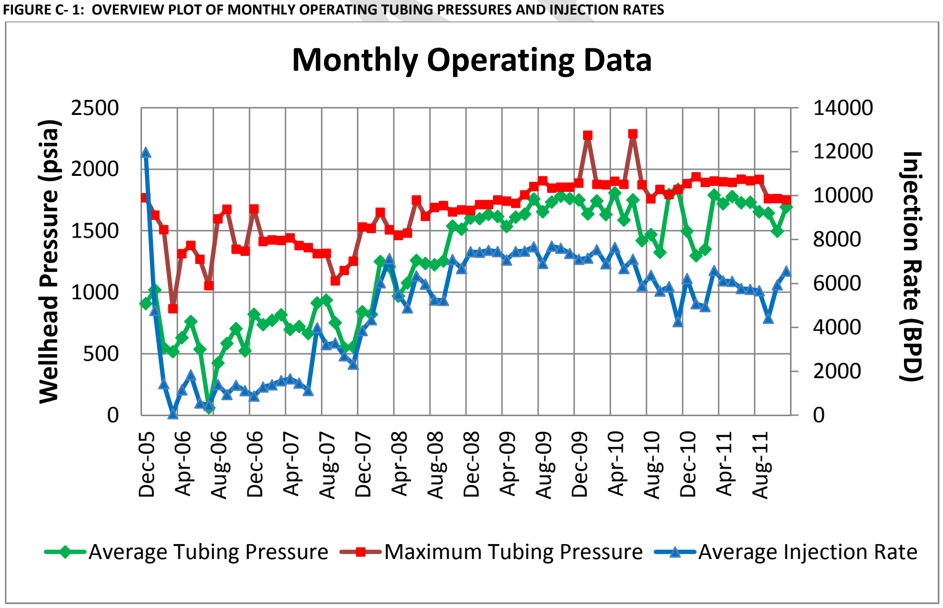
Operational data are analyzed using the steady state radial flow equation, in the form of the Hall integral and its derivative, while pressure transient tests are analyzed using solutions to the radial diffusivity equation. Operational data includes both injection rate and pressure information, but actual data reported can vary depending on the regulatory agency requirements. For example, injection volumes may be reported with daily, monthly, or quarterly frequency. Injection pressures may be reported a number of ways, such as a maximum value and a monthly average or as monthly minimum and maximum values.

For best applicability, surface pressures should be converted to bottomhole conditions, prior to performing a Hall plot analysis. This conversion requires the analyst account for friction pressure loss with a correlation, such as Hazen-Williams (Westaway and Loomis, 1977; Lee and Lin, 1999), based on the tubing specifics and injection rates. The hydrostatic pressure from the brine column must be added to the surface pressure as part of the bottomhole pressure calculation. The reporting frequency of injection rates can also impact the quality of the analysis. Plots, calculations, and analyses associated with operational data are summarized below:

Operating Rates and Pressures Overview Plot

- Overview of surface pressures and injection rate or volume plot (Figure C-1)
    - Cartesian (linear) plot of surface injection pressure and rate/volume versus date
        - y-axis primary: average and maximum wellhead (surface or tubing) pressure
        - y-axis secondary: average injection rate (barrels per recording time period)
        - x-axis: date (based on recording timeframe, e.g., daily, monthly, quarterly)

FIGURE C- 1: OVERVIEW PLOT OF MONTHLY OPERATING TUBING PRESSURES AND INJECTION RATES



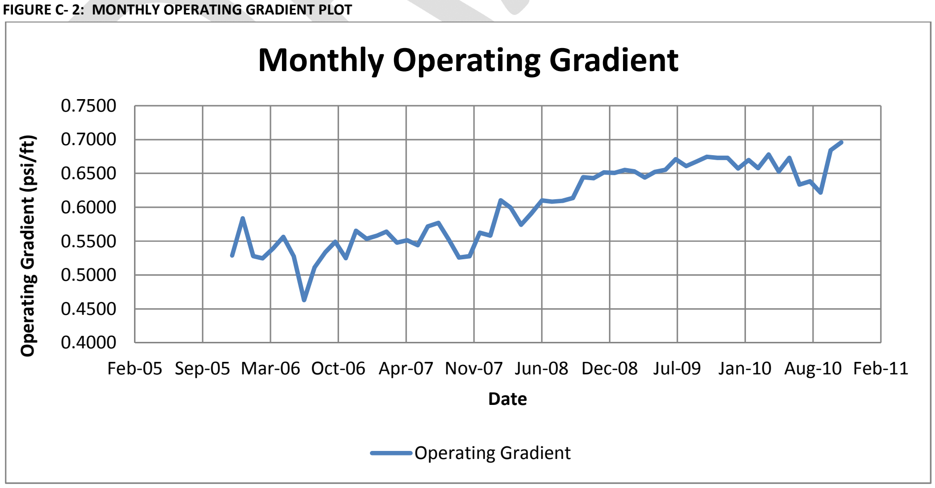
- Purpose
    - Identifies trends or large changes in pressure and/or injection rate/volume behavior
    - Provides a timeline of operational activity
- Challenges: Frequency of data reported, intermittent well use, quality of data

- Possible red flags
  - Maximum pressures nearing fracture pressure
  - Increased pressure with declining injection rates
  - Suspect data quality (e.g., repeating pressure value with varying rate)

OPERATING PRESSURE GRADIENT PLOT

- Cartesian plot of the operating bottomhole pressure (BHP) gradient (Figure C-2)
  - The operating BHP can be measured or calculated
  - Calculated values obtained by adding the hydrostatic fluid column, based on brine specific gravity, to the surface tubing pressure and subtracting friction pressure loss
    - Calculate hydrostatic pressure of the fluid column:
      - (disposal brine specific gravity) x (fresh water gradient) x (depth)
    - Brine specific gravity is obtained from a fluid analysis or is estimated
    - Friction loss estimated using tubing dimensions and Hazen-Williams friction loss correlation (Lee, et.al., 1999; Westaway, et.al., 1977)
      - Tubing friction factor, C, is based on tubing type
      - Frequency of rates data impact friction calculations
  - Operating pressure gradient is operating BHP divided by depth (psi/ft)
    - Depth is the top of the completed interval or tubing depth
  - Cartesian plot of bottomhole operating pressure gradient versus date
    - y-axis: operating pressure gradient, psi/ft
    - x-axis: date (based on recording timeframe, e.g., daily, monthly, quarterly)

FIGURE C- 2: MONTHLY OPERATING GRADIENT PLOT



- Purpose
    - Compare operating pressure gradient to calculated or measured area specific fracture gradients to confirm the disposal well is operating below fracture pressure
- Challenges
    - Conversion of surface pressure to BHP can be inaccurate
    - Varying injectate specific gravity introduces uncertainties in calculation of the hydrostatic fluid column
        - More of a concern in commercial disposal wells
    - Friction pressure estimates can be suspect, especially for wells with high injection rates through smaller diameter tubing
    - Frequency of rate data impacts friction calculations
- Possible red flags
    - New or extension of fractures may occur if well is operating above the fracture gradient
    - Tubing size and injection rates are not within the table range for calculating friction loss values

Hall Integral and Derivative Plot

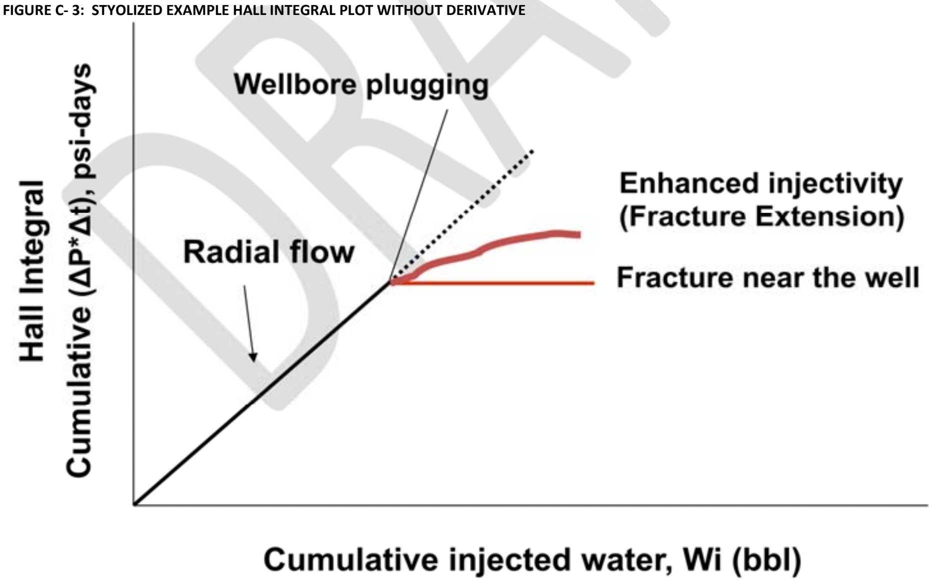
The Hall integral has been used since 1963 (Hall, 1963; Jarrell, et.al, 1991). The Hall integral derivative evolved later after the derivative approach was developed for well testing techniques (SPE paper No. 109876 by Izgec and Kabir, 2009). The Hall plot uses readily available operational data coupled with an estimate or measurement of the average static reservoir pressure prior to injection. This operational data is routinely recorded as part of UIC permit compliance.

The Hall plot represents a graphical integration of the steady state radial flow equation which couples operating pressure and cumulative injection. Pressure values are calculated on a bottomhole (BHP) basis for use in the Hall Plot. The Hall Plot is a numerical integration between the operating BHP and static (reservoir) BHP. This numerical integration yields a straight line trend for radial flow. The integral (summation) serves to “smooth out” noise commonly present in injection operating data. The derivative is the running slope of the Hall integral plot. The derivative magnifies any slope change and tends to be much noisier than the Hall integral. Adding the derivative trend to the integral plot helps to more readily identify significant changes in disposal well behavior.

The Hall integral is accepted reservoir engineering methodology that is easily calculated in a spreadsheet. The integral provides a much longer observation period of the injection zone than is generally obtained with a pressure transient test. The Hall integral is a function of the pressure difference between injection and shut-in conditions weighted by operating time increments.

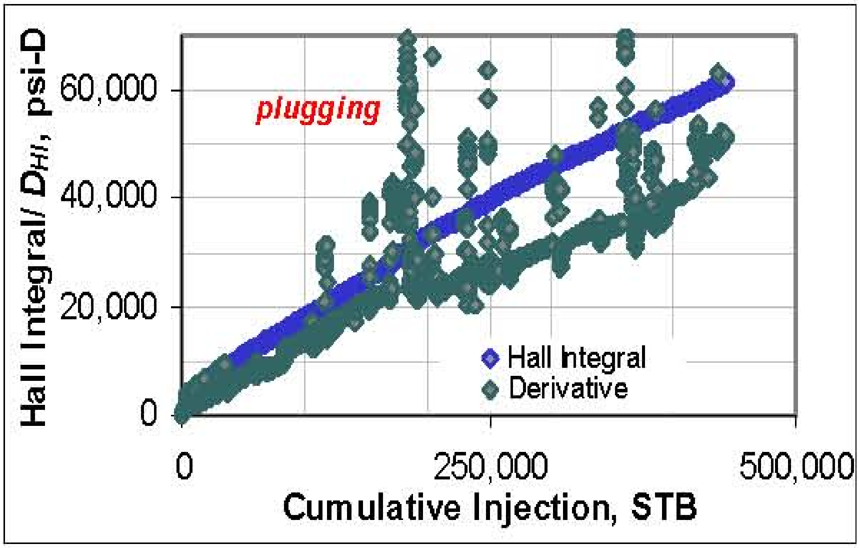
- Cartesian (linear) plot of Hall Integral and Derivative curves (Figure C-3)
    - Hall integral is a numerical integration between the operating BHP and static (reservoir) BHP
        - Tracks the change in operating pressure with time, compared to the initial static conditions
        - Cumulative or running summation of (ΔP*Δt) as well operates
            - Values will increase with cumulative operation time
        - ΔP: Injecting BHP-static BHP calculated for each measurement
        - Δt: Time increment for measurements matched to ΔP calculation
    - y-axis: Hall integral (H_I) = Cumulative (ΔP*Δt) function, psi - time period
    - y-axis: Hall Integral Derivative: $D_{HI} = (H_{i2}-H_{i1})/(Wi_2-Wi_1)$
        - ($H_{i2}-H_{i1}$) represents difference between successive Hall integral values
        - (Wi_2-Wi_1) represents difference between successive cumulative injection values
    - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE C- 3: STYOLIZED EXAMPLE HALL INTEGRAL PLOT WITHOUT DERIVATIVE



fracturing

FIGURE C- 4: HALL INTEGRAL PLOT WITH DERIVATIVE (MODIFIED FROM FIG 1 FROM YOSHIOKA, ET.AL, 2008, WITH PERMISSION)



- Purpose
  - Evaluates injection well performance and reservoir flow behavior or changes in behavior over time
    - Slope change on the Hall integral trend reflects the pressure response as fluid moves radially from the disposal well
      - Slope indicates a well's completion condition or injection efficiency
      - Negative slope break associated with enhancement of injectivity
      - Positive slope break indicates reduced injectivity
      - No slope break (straight line) represents radial flow
  - Location of derivative (D_{HI}) relative to the Hall integral (H_I) also indicates the completion condition of the well
    - Highlights well behavior patterns
      - D_{HI} located below H_I indicates enhanced injectivity or fracturing
      - D_{HI} overlying H_I indicates radial flow
      - D_{HI} above H_I suggests a decrease of injectivity or plugging
    - Hall derivative (D_{HI}) should always be a positive value if Hall integral (H_I) is increasing
- Challenges:
  - Available time increment of pressure and injection reported data impacts quality of Hall derivative function and shape of plot

- Requires an initial reservoir pressure
    - A measurement or valid estimate of average initial static BHP is required
- Conversion of surface pressure to BHP can be inaccurate
    - Friction pressure estimates can be suspect, especially for wells with high injection rates through smaller diameter tubing
- Hall integral should increase as long as injection is occurring
    - Too high static reservoir pressure estimate can cause negative increments in the Hall integral calculation
- Wells used intermittently require data manipulation to keep the Hall integral positive

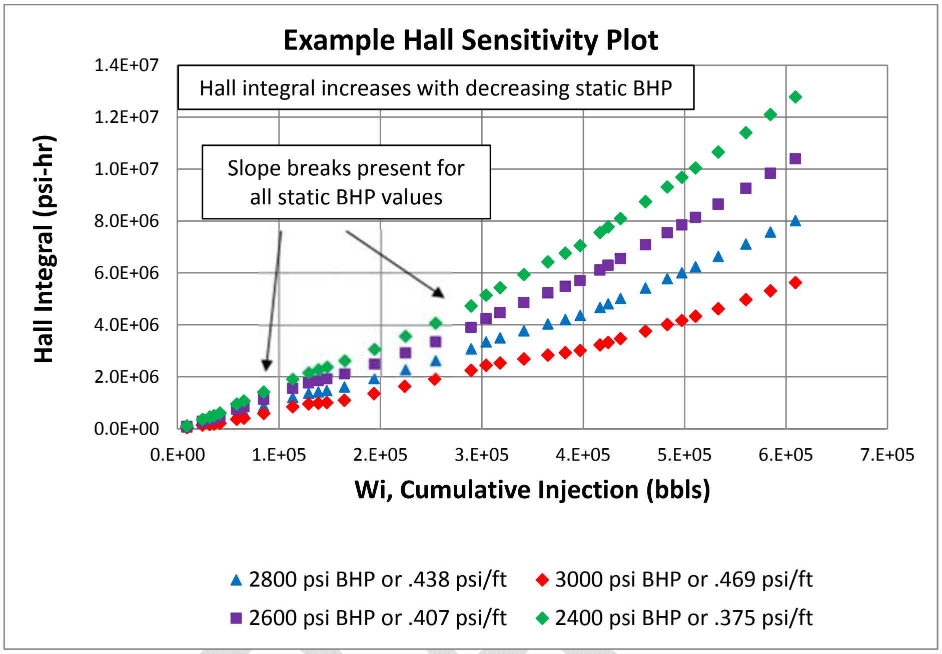
- Possible red flags
    - Data quality – Constant tubing pressure with varying injection volumes
    - Length of time increment for reporting frequency – Monthly versus daily
    - Negative slope break may be associated with fracturing of the well

Hall Integral Sensitivity Plot

Sensitivity calculations were performed on each of the case study wells using a range of assumed bottomhole static pressures to explore the impact of static pressure assumption on Hall plot behavior. Even with varied pressure assumptions, the overall slope change trend in each well was not impacted, but the degree of slope change did vary with the static pressure assumed. The WG concluded an incorrect static pressure may not critically alter the Hall plot qualitative meaning, though it would have a quantitative impact. For purposes of the case studies, the Hall plots were used for qualitative behavior assessment only.

- Linear plot of Hall Integral with varying initial pressures(Figure C-5)
    - Checks the sensitivity to a range of original reservoir static pressures
    - y-axis: Hall integral (H_I) = Cumulative ($\Delta P*\Delta t$) function (psi- time period)
    - x-axis: Cumulative injection volume, W_i (barrels)

FIGURE C- 5: EXAMPLE HALL INTEGRAL SENSITIVITY PLOT



- Purpose:
  - Qualitative assessment of estimated static pressure estimate on character or shape of Hall integral trend
    - Hall integral becomes larger with decreasing initial static pressure due to increased pressure difference between injection and initial shut-in pressures
- Challenges:
  - Negative increment in the Hall integral may occur if initial pressure assumption is too high

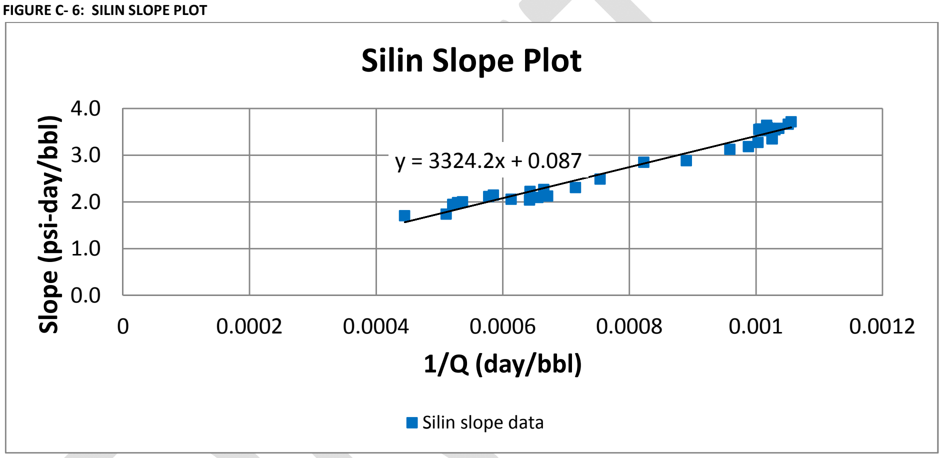
Silin Slope Plot

Silin Slope plot is used to determine average reservoir pressure around an injection well using injection pressures and rates. Operational injection data are plotted on a linear plot of wellhead pressure/injection rate versus reciprocal of injection rate. The resulting data points are fitted to a best fit straight line with the line's slope yielding a mean reservoir pressure around the disposal well. The resulting average reservoir pressure can then be used to develop a Hall plot. The Silin plot is designed as a method for monitoring reservoir pressure in active waterfloods and is only applicable to radial flow situations.

Silin Slope plots were performed on each of the case study wells. In some cases, an estimate of average disposal reservoir pressure was available from fluid level data. The results of the Silin plots were compared against available measured pressures and generally predicted too high a reservoir pressure. The high Silin Plot predicted pressures resulted in a negative Hall integral increment; consequently, the Silin plots were not included in the case study analyses.

- Linear plot of injection well operating data (Figure C-6)
    - Y-axis: Injection BHP divided by daily injection rate, P_{wf}/Q (psi-time period per barrel)
    - X-axis: Reciprocal of the injection rate, 1/Q (day per barrel)

FIGURE C- 6: SILIN SLOPE PLOT



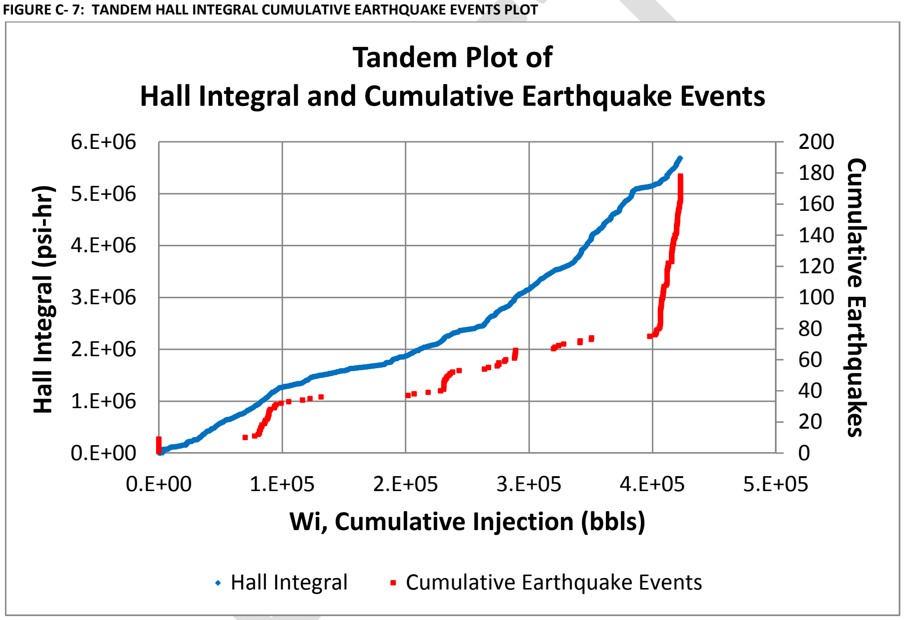
- Purpose
    - Developed as a modification to Hall plot analysis to determine mean reservoir pressure around the injection well
- Challenges:
    - Rate fluctuations in operational data can cause data scatter
    - Method is applicable at very early times during the infinite-acting period
        - Faults or fractures may introduce error in assumptions for applicability
- Possible red flags
    - Data quality may cause a scattered plot
    - Unrealisitic static reservoir pressure

TANDEM PLOT COMBINING HALL INTEGRAL WITH SEISMIC EVENTS

The tandem plot is designed to graphically compare the Hall integral response to a cumulative count of seismic events within a selected radial search area.

- Cartesian (Linear) Tandem Plot (Figures C-7)
  - Plot Hall integral and cumulative earthquake events vs. cumulative injection
    - y-axis primary: Hall integral (H_I) = Cumulative ($\Delta P * \Delta t$) function (psi-time period)
    - y-axis secondary: Cumulative earthquake events (count)
    - X-axis: Cumulative injection volume, W_i (bbls)

FIGURE C- 7: TANDEM HALL INTEGRAL CUMULATIVE EARTHQUAKE EVENTS PLOT



- Purpose:
  - Plot provides a combined graphic of injection well behavior to number of seismic events
- Challenges:
  - Creating cumulative injection history for cumulative earthquake events
    - Selecting size of seismic monitoring area around disposal well
    - Acquiring seismic data from various databases
    - Linking earthquake events to cumulative injection based on event date

- Increase in events may be delayed owing to late deployment of additional seismometers
- Deciding what lower magnitude limit is needed for count of seismic events

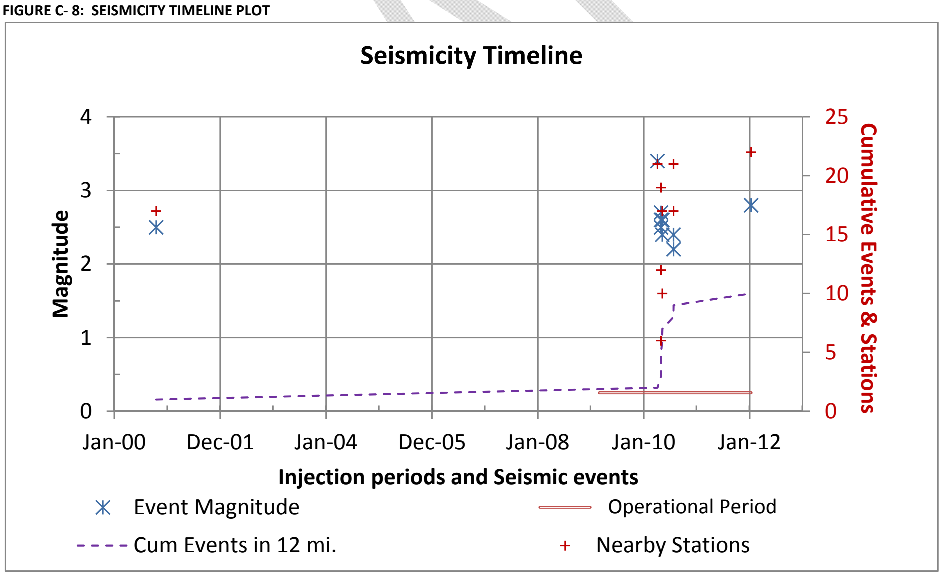
- Possible red flags
  - Correlation between injection well response (Hall integral slope change) and number of seismic events

SEISMICITY TIMELINE

Plot created to compare event magnitude, cumulative seismic events, number of seismometers, and disposal well operational period

- Seismicity Timeline Linear Plot (Figure C-8)
  - Plot of the earthquake magnitude and cumulative earthquake events versus the operational period of the disposal well
    - Primary Y-axis: Earthquake magnitude
    - Secondary Y-axis: Earthquake cumulative events and number of recording stations
    - X-axis: date and disposal well operational period

FIGURE C- 8: SEISMICITY TIMELINE PLOT



- Purpose:
  - Provide a common plot of seismic response and monitoring stations with disposal activity

- Challenges:
    - Selecting size of monitoring area around disposal well
    - Acquiring seismic data from various databases
    - Acquiring number of monitoring stations within the selected monitoring area
- Possible red flags
    - Correlation between operational period of disposal well and occurrence or number of seismic events
    - Seismic event background level prior to disposal well operations to determine if induced
    - Number of seismometers relative to number of seismic events

Overview of Pressure Transient Testing for Disposal Wells

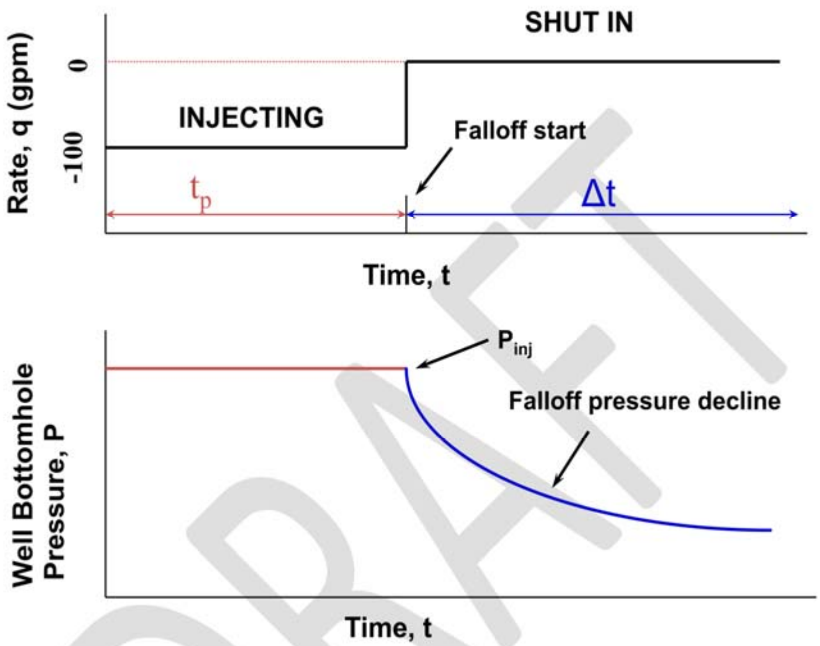
Pressure transient theory correlates pressures and rates as a function of time and is the basis for many types of well tests including both falloff and step rate tests. Pressure transient test analyses revolve around solutions to a partial differential equation, called the radial flow diffusivity equation. These solutions provide an injection well behavior model, a method for reservoir parameter evaluation, and allow calculation of pressure and rate as a function of distance.

The most common solution used applies only to radial flow. However, this solution is not applicable in all geologic or well completion situations. By solving the diffusivity equation for boundary conditions to address these geological or completion situations present at the wellbore or in the reservoir, mathematical solutions (type curves) specific to these situations are obtained. Since these reservoir model solutions are based on a differential equation, their "signature" is best presented in a log-log plot format.

Pressure transient tests provide a more refined look at the reservoir and well completion characteristics. Pressure transient tests run in disposal wells include falloff and step rate tests. Pressure transient tests are typically shorter in duration than the operational data analysis, but generally designed to provide a better reservoir description.

One type of pressure transient test commonly associated with a disposal well is a falloff test that measures the pressure decline by recording the well surface or bottomhole pressure (BHP) after the well is shut-in. Falloff tests are to a reservoir engineer as seismic surveys are to a geophysicist. Pressure transient tests provide short and intermediate distance mathematical "pictures" of the reservoir nature around the well when the data is analyzed against existing reservoir models and would be analogous to "a short term pinging of the reservoir with sonar" in the form of a pressure wave, whereas seismic surveys are acoustical "pinging" of the reservoir. Both use some type of energy wave to probe through the reservoir much like sonar "pings" the ocean or radar "pings" the airways. In both instances, the reservoir response to the associated "wave ping" is measured and analyzed. A falloff test sequence of events and pressure response is shown in Figure C-9.

FIGURE C- 9: FALLOFF TEST SEQUENCE OF EVENTS AND PRESSURE RESPONSE



Another type of pressure transient test commonly associated with a disposal well is a step rate test. Step rate tests are a direct method of estimating fracture pressure and fracture gradient (formation parting pressure) of the injection interval. Step rate tests can be analyzed for both fracture gradient and reservoir characteristics. Step rate testing consists of a series of constant rate injection steps with each step being maintained for an equal duration of time as shown in Figure C-10 with corresponding pressure increases as illustrated in Figure C-11. Ideally, the injection pressure should be stabilized at the end of each rate step.

FIGURE C- 10: STEP RATE TEST RATE SEQUENCE

FIGURE C- 11: STEP RATE TEST PRESSURE SEQUENCE

Analysis of Disposal Well Pressure Transient Tests

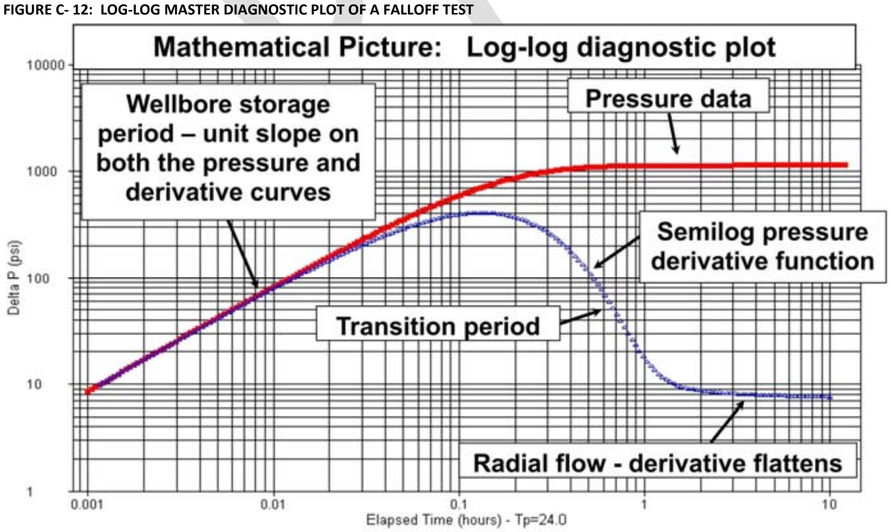
Analysis of both falloff and step rate tests involve pressure transient analysis techniques. Common methodology can be applied to each of these two tests. Falloff test analysis typically requires specialized software. Step rate tests can be analyzed using a spreadsheet, though a more detailed analysis may also necessitate the use of specialized software. Details relating to the analysis of each type of test are provided below.

Falloff Testing

The first step to analyzing a falloff test is plotting the data in a format that allows for comparison against the known reservoir model solutions to the unsteady state radial diffusivity equation. To compare site specific test data to these solutions requires plotting the actual data in a log-log plot format, as shown in Figure C-12. Therefore the log-log plot becomes a useful diagnostic tool to see patterns of behavior at the well and into the reservoir. These patterns indicate the presence of different flow regimes.

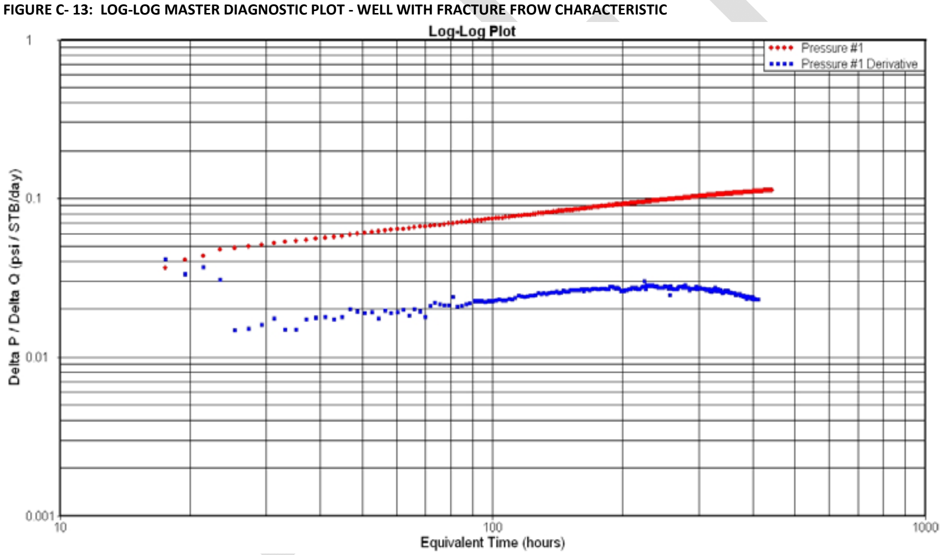
By identifying the flow regimes through a “mathematical picture” on the log-log plot, reservoir model solutions can then be matched to the test response to characterize the reservoir. The solutions to the reservoir flow models are plotted in the same log-log format, so finding the correct reservoir model becomes a picture matching process between the plotted test data and known reservoir responses.

FIGURE C- 12: LOG-LOG MASTER DIAGNOSTIC PLOT OF A FALLOFF TEST



- Log-log diagnostic plot (Figures C-12 and C-13)
    - Logarithmic y-axis:
        - Pressure change, ΔP
            - Subtract the final measured pressure at the end of injection period from each pressure value during the falloff period
            - ΔP increases as pressure declines during the falloff test
        - Pressure derivative, P'
            - Running slope calculated from a semilog plot of falloff pressure versus elapsed test time
    - Logarithmic x-axis:
        - Elapsed test time, Δt, starting from when well is shut in
        - Time function is modified if the injection rate varied significantly prior to the falloff

FIGURE C- 13: LOG-LOG MASTER DIAGNOSTIC PLOT - WELL WITH FRACTURE FROW CHARACTERISTIC



- Purpose
    - Final falloff pressure provides a static formation pressure measurement
    - Arranges test data in reservoir model format or mathematical "picture"
    - Derivative curve provides a "magnified" look at reservoir transient responses
        - Enhances identification of various flow regimes
        - Couples the log-log and semilog plot
            - Derivative curve is the running slope of the semilog plot

    - Provides reservoir characteristics
        - Identify flow regimes
            - Derivative flattens during radial flow (See Figure C-12)
        - Identify reservoir boundaries, if located near the well
    - Measures the transmissibility of the injection zone or reservoir pathway
        - Transmissibility is the formation’s ability to transmit pressure
        - Directly relates to the amount and lateral extent of pore pressure buildup
    - Indicates well completion condition
        - Spacing between the pressure and pressure derivative curves
        - Dimensionless wellbore skin factor describes the well completion condition
            - Negative skin: Enhanced completion
            - Positive skin: Damaged completion
            - Fractured wells exhibit very negative skin factors (-5 to -6)
- Challenges
    - Planning of test to obtain good quality data
    - Quality of recording devices to reduce data scatter
    - Duration of test sufficient to see beyond wellbore effects and identify reservoir characteristics
    - Special pressure transient software needed to analyze test
    - Handling of wastewater for duration of the test
- Possible red flags
    - Non-radial flow behavior may suggest pressure not dissipating radially from well
    - Lower permeable reservoirs may require longer test times
    - Unanalyzable test – planning or data collection issues

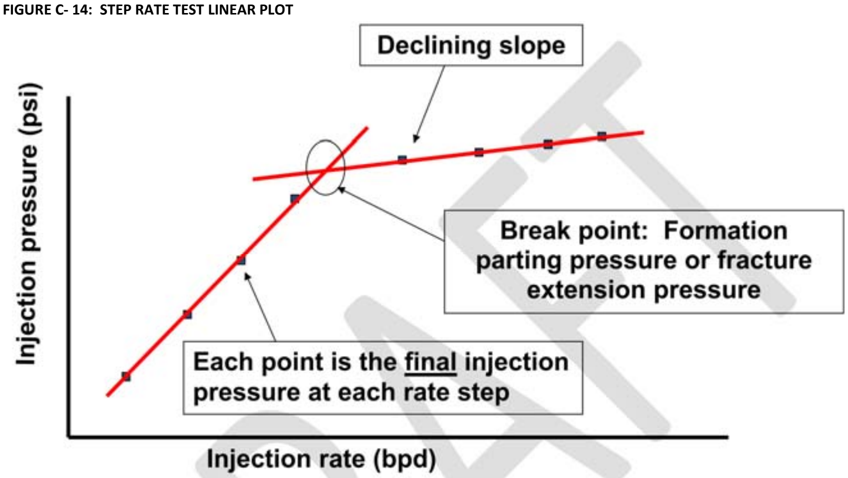
Step Rate Tests

Whereas falloff tests involve shutting in of the disposal well, a step rate test is conducted during operation of the well. Step rate test data can be analyzed either as a composite data set or through individual rate step analyses. Analysis of the composite approach involves a linear plot while injectivity analysis of individual rate steps involves a more complex log-log plot analysis of each rate step. If both methods are performed, the results can be compared for agreement. The injectivity analysis is similar to the falloff test analysis except pressures are increasing during each rate step instead of decreasing as in a falloff test. However, the limited duration of each rate step results in a shallower look into the reservoir. The goal of both analyses is to determine the reservoir formation parting (fracture) pressure.

Linear Plot

- Linear plot of injection pressure versus injection rate (Figure C-14)
    - y-axis: Final injection pressure of each rate step
        - Bottomhole pressure
    - x-axis: Constant injection rate of each rate step

FIGURE C- 14: STEP RATE TEST LINEAR PLOT



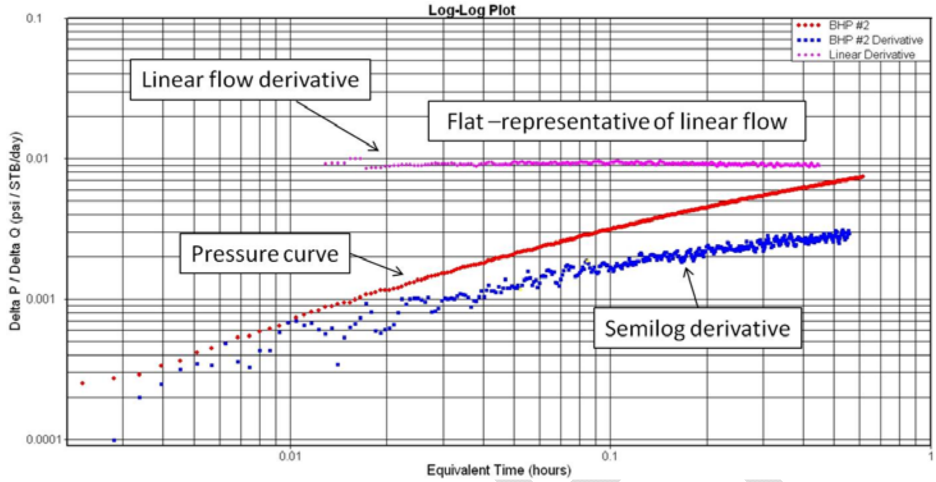
- Purpose
    - Identify formation parting pressure for use in determining maximum allowable operating pressure for disposal well
        - Review data for slope changes by drawing straight line(s) through data points
            - Negative slope break suggests enhanced injectivity or fracturing
            - No slope break
                - Fracture pressure not observed during test
                - Start pressure exceeded fracture pressure
    - Confirm well is operating below the fracture pressure gradient
- Challenges:
    - Surface pressure measurements may provide misleading results
        - Friction effects can mask the slope break
    - Conversion of surface pressures to bottomhole pressure
        - Must account for friction pressure
        - Friction calculation often in error for wells with high injection rates through smaller diameter tubing

- No break may be observed if disposal well is fractured prior to the first rate step
    - Starting injection rate too high
- Insufficient number of rate steps are included in the test to establish straight lines on the linear plot
- Stabilized pressures are not reached during each rate step
- Constant injection rates are not maintained during each rate step
    - Test typically requires a pump truck
    - Access to additional fluid volumes for continuous injection
- Use of continuous pressure and rate recording data throughout the test
    - Allows confirmation of pressure stabilization during each rate step
    - Allows each rate step to be analyzed as an injectivity test

Injectivity Plot

- Log-log injectivity plots of each rate step (See figure C-15)
    - Logarithmic y-axis:
        - Pressure change, ΔP
            - Subtract the pressures measured during injection period of each rate step from the final pressure from the preceding rate step or shutin pressure for analysis of the first rate step
        - Pressure derivative, P’
            - Running slope of a semilog plot of test data
    - Logarithmic x-axis:
        - Superposition time function to account for changing injection rates during the test

FIGURE C- 15: INDIVIDUAL RATE STEP LOG-LOG INJECTIVITY PLOT



- Purpose
  - o Identifies flow regime during each rate step
    - Review each step for fracture signature or fracture extension based on fracture half length
    - Fracture signature suggests formation parting pressure exceeded
- Challenges
  - o Conversion of surface pressures to bottomhole pressure required for analysis
    - Must account for friction pressure
    - Requires continuously recorded downloadable electronic data
  - o Data can be “noisier” since injection is occurring and passing by the pressure gauge
  - o Requires pressure transient software for analysis

HOW CAN THE OPERATIONAL DATA AND PRESSURE TRANSIENT TEST ANALYSES BE USED?

Pressure change in the reservoir can induce seismicity in certain geologic settings. The reservoir engineering approaches may be useful for linking the pressure behavior of the injection well to seismicity and area geology for assessing if a reservoir is appropriate for a disposal zone. Pressure transient testing identifies flow behavior which indicates how the reservoir pathway pressure increases are distributed away from the disposal well and, in the case of a falloff, measures static pressure for assessing reservoir pressure buildup. For example, pressure increases from a disposal well exhibiting a fracture or linear flow characteristic may extend directionally over greater distances from the well than would be expected for radial flow.

One aspect of assessing induced seismicity concerns is the distance pressure buildup influence can be transmitted in the disposal reservoir. Two aseismic examples of large distance pressure influence are provided in Appendix H. One example highlights preferential pressure distribution over great distances in a formation suspected of containing a geologic anomaly and the second example illustrates the cumulative pressure buildup from multiple disposal wells injecting into the same formation.

For disposal wells identified as injecting into linear or fractured flow regimes, expanding the area reviewed may be useful to describe potential reservoir behavior. Typical pressure buildup calculations are based on the assumption that injection occurs into a radially, homogeneous, infinite acting reservoir. Naturally fractured reservoirs generally do not meet these assumptions. Therefore, pressure buildup distribution from a disposal well injecting into a fractured formation may require a more complex evaluation than for wells injecting into a formation exhibiting radial flow characteristics. In a homogeneous reservoir, the pressure dissipates equally in all directions away from the wellbore, however the cumulative pressure effects from multiple disposal wells injecting in the same formation may enlarge the area of pressure influence. Though the radial flow equations are applicable, modifications may be necessary to account for multiple pressure sources.

Analysis of the operating data coupled with any available pressure transient tests such as falloff and step rate tests for a disposal well may provide critical details, both geologically and hydraulically, about the nature and conditions on the injection reservoir. An attempt should be made to correlate anomalous test results to area seismic events to determine if additional data gathering, monitoring, or testing is warranted. Since operating data are readily available and require no additional monitoring, the reservoir engineering approach for analysis of such data provides an established technical methodology that may correlate existing well data to seismic events in the area.

How did the WG perform the case study reservoir engineering evaluations?

The detailed assessment for each case study is included in the respective case study appendices. While many of the methods used were highlighted during the preceding discussions, the software and tasks performed on the case study examples are outlined below. The software listed represents what was available to the WG, but other options are available.

- Software requirements
    - Microsoft Excel® was used for the evaluation of operational data
        - Required assumptions to generate some parameters or functions used
    - PanSystem® software was used to analyze pressure transient data
        - Other pressure transient test software could be used

- Tasks performed for all case study areas
    - Obtained injection pressure, rate, and time data for wells within the areas
    - Operational analysis plots generated:
        - Overview plot
        - Operating gradient plot
        - Hall integral plot with derivative
        - Tandem plot
            - Relates cumulative earthquakes to Hall integral
    - Pressure transient test (falloff and step rate) analysis plots generated when data available:
        - Cartesian overview plot
        - Log-log plot
        - Type curve match where applicable
        - Step rate test linear plot

CITATIONS

Hall, H.N., 1963, How to analyze waterflood injection well performance: World Oil, October 1963, p 128-130.

Izgec, B., and Kabir, C. S., 2009, Real-time performance analysis of water-injection wells: SPE Reservoir Evaluation & Engineering, v. 12, no. 1, p. 116-123.

Jarrell, P.M. and M.H. Stein; 1991, Maximizing Injection Rates in Wells Recently Converted to Injection Using Hearn and Hall Plots; SPE Paper 21724, 1991.

Lee, C.C. and S.D. Lin, Handbook of Environmental Engineering Calculations, McGraw-Hill, p. 1.278-1.280, 1999.

Westaway, C.R. and A.W. Loomis; Cameron Hydraulic Data, Ingersoll-Rand Company, p. 3-6 through 3-8, 1977.

Yoshioka, K., Izgec, B. and Pasikki, R., 2008, Optimization of Geothermal Well Stimulation Design Using a Geomechanical Reservoir Simulator: PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2008, SGP-TR-185.

APPENDIX D: NORTH TEXAS CASE STUDY AREAS: DFW AND CLEBURNE

BACKGROUND

Several small (Magnitude 1.7 to 3.3) earthquakes occurred in the central part of the Dallas - Fort Worth metroplex near DFW international airport starting on October 31, 2008. The two case study wells in this area began operations in June 2007 and March 2008. Seismic activity (Magnitude 2.0 to 3.3) near the town of Cleburne started on June 2, 2009. The seven case study wells in this area began operations between October 2003 and August 2007. Both areas are located in north central Texas and the eastern portion of the Barnett shale play (Figure D-1).

GEOLOGIC SETTING

The DFW and Cleburne case studies are located within the Fort Worth Basin. The generalized east-west cross-section (Figure D-2) shows the relationship of the formations bounded on the east by the Ouachita thrust fault against basement rocks. The generalized north-south cross-section in Figure D-3 shows Pennsylvanian age faulting (Bruner and Smosna, 2011). A third faulting style appears in the basin, resulting from collapsed chimney structures above Ellenburger karst sink holes and caverns illustrated in Figure D-4 (Bruner and Smosna, 2011;

McDonnell, 2007; Montgomery et al., 2005; Steward, 2011). The case study Class II disposal wells are completed in the Ellenburger formation.

The Barnett Shale lies below the Mississippian-Pennsylvanian unconformity, and lies unconformably over Ordovician carbonates (Viola, Simpson and Ellenburger formations). As shown in Figures D-2 and D-3, the Barnett shale can lie directly on the Ellenburger.

During a meeting between EPA Region 6 and an area operator, the operator presented geologic data gathered in portions of the Fort Worth Basin which indicated there are no obvious Ellenburger karst features in the DFW airport area; however, the area around Cleburne showed significant karst features. The presentation displayed a major normal fault with approximately 600 feet of displacement, down to the east-southeast, in the DFW area. This fault is located about a mile west of the Ellenburger disposal well, DFW C1DE.

Oil and Gas Activity

The Barnett Shale production discovery took place in 1981 in Newark East field, in Wise County. Since 2002, most Barnett shale wells are horizontally drilled with 1000 to 3500 foot lateral legs (Martineau, 2007). In Newark East, the top Barnett Shale depth ranges from 6900 to 7500 feet, with a thickness varying from 200 to over 700 feet near the Muenster Arch in the northeast (Montgomery et al., 2005).

History of Seismicity

Prior to October 2008, no earthquakes were reported in any of the six seismicity databases, (ANSS, SRA, NCEER, USHIS, CERI and PDE), within 40 miles of the Dallas Fort Worth international airport or the Cleburne area.

Reservoir Engineering Data Collected

The RRC website provides public access to downloadable permitting-related documentation and annual operating reports. Permitting documents provided details concerning completion depths, construction information, and permit conditions for the case study wells. Annual operation reports provided monthly injection volumes and average and maximum wellhead pressures.

Data Reviewed and Processed for Reservoir Engineering Analysis

Surface pressures were converted to approximate bottomhole pressure (BHP) at tubing seat depths. For this conversion, a brine specific gravity of 1.05 (roughly equivalent to 45,000 ppm chlorides) was assumed. Tubing dimensions, length and inside diameter, were taken or estimated from permit documentation. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 100 for steel tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. After operating BHPs were estimated from the reported tubing pressures, seven operating data-related plots were prepared for selected wells within the case study areas. The seven plots were a seismicity timeline; an operational overview data plot; operating pressure gradient plot; a Hall integral and derivative plot based on the average tubing pressure; Silin slope plot; and a tandem plot. The tandem plot combines the Hall integral with cumulative area earthquake events against a common scale of cumulative disposal volume.

Operational Analysis Objectives

Operational analysis plots were prepared to assess well operating data. Details about the following plots were previously discussed in Appendix B:

- Seismicity timeline
- Operational data overview plot
    - Identify trends in the basic operating data such as increased surface pressure or injection volumes over the well's life
- Operating gradient plot
    - Indicator of whether a well's operating pressure approached a rule of thumb fracture gradient value of 0.7 psi/foot
    - Calculated by dividing the computed operating BHP by the depth of the most recent tubing seat value
    - Generally, tubing seats were within 100 feet of the top of the completion interval in each well
- Hall integral plot
    - Assess injectivity enhancements
    - Requires estimate of average reservoir pressure
    - Sensitive to the average pressure value used
- Silin slope plot
    - Estimate average pressure around the injection well
    - Silin result compared to assumed value in Hall integral calculation
- Tandem plot
    - Correlate earthquake events to operational data
        - Plot Hall Integral and cumulative earthquake events
            - Cumulative earthquake events multiplied by factor to scale the event trend to magnitude of cumulative water injection volumes
        - Plot operational rate history and earthquake events

DFW Airport Case Study Area

The DFW airport area earthquake swarm, within a five mile radius of the case study wells discussed below, is shown in map view on Figure D-5, and in seismicity timeline form of events on Figure D-6. No earthquake events were located within 5 miles of DFW North A1DM. Figure D-7 shows the earthquake events within a 5 mile radius of DFW C1DE. The figures are based on information from the ANSS and NEIC catalogs, plus the SMU portable arrays that were described by Frohlich et al. (2011). While Eisner discusses seismic information recorded by Chesapeake (Eisner, 2011), details were not provided so this information was not incorporated in this report.

TABLE D-1: DFW AIRPORT AREA SESIMICITY THROUGH 1/31/2012

Year	Starting Event	Number of Events	Magnitude			Ending Event
			Min.	Avg.	Max.	
2008	10/31/2008	19	1.7	2.4	3.0	12/1/2008
2009	5/16/2009	4	2.6	2.9	3.3	5/16/2009
2010		0				12/31/2010
2011	8/7/2011	1	2.6	2.6	2.6	8/7/2011
2012		0				1/31/2012

The following two wells were investigated by the Railroad Commission of Texas (RRC), in response to the earthquakes starting in 2008. Both suspect wells were disposal wells completed in the Ellenburger formation. The wellbore diagram for the DFW C1DE is shown in Figure D-8. Permit information is summarized in Table D-2 and listed below:

DFW Airport Vicinity Disposal Wells

DFW C1DE: UIC Permit 97642; Maximum permit pressure of 5023 psig and injection rate of 25,000 BPD; Total depth 14,375’; Initial injection September 2008; Final injection August 2009; Authorized injection zone 10,047’-14,375’ open-hole; Injection formation - Ellenburger; Current well status - shut-in.

DFW North A1DM: UIC Permit 98402; Maximum permit pressure of 4400 psig (amended from 4575) and injection rate of 25,000 BPD; Total depth 13,165’; Initial injection November 2007; Authorized injection zone 8,802’-13,165’; Injection formation Ellenburger.

TABLE D-2: DFW AIRPORT AREA DISPOSAL WELL CONSTRUCTION

Well	Total Depth	Long String Casing Diameter and Seat	Tubing Diameter and Seat Depth	Perforations
DFW C1DE	14,375’	7” to 10,047’	4 ½” to 9997’	Open-hole 10,047’-14,375’
DFW North A1DM	13,165’	7” to 8,800’	4 ½” to 8800’	Open-hole 8802’ – 13,165’

Operational Analysis Plots and Observations

Only operational data was available so no pressure transient test analyses were conducted in the two DFW airport area case study wells. Figures D-9 through D-12 provide an operational data overview and calculated operational pressure gradient plots for both wells. Figures D-13 and D-14 are Hall integral with derivative plots and Figures D-15 and D-16 are the Silin slope plots for each well. Table D-3 summarizes data associated with the Hall integral and Silin slope plot and compares the average pressure estimated for the Hall integral to the value determined from the corresponding Silin slope plot.

TABLE D-3: DFW AIRPORT AREA HALL AND SILIN SLOPE PLOT RESULTS

Well	Hall Assumed Average Pressure (psi)	Slope Plot Average Pressure (psi)
DFW C1DE	4600	6533
DFW North A1DM	3900	5206

DFW C1DE

- Overview plot (Figure D-9)
    - Well shut-in during August 2009
- Operating pressure gradient plot (Figure D-11)
    - Remained below the 0.7 psi/ft rule-of-thumb fracture gradient
- Hall integral and derivative plot (Figure D-13)
    - Indicated normal injection
- Silin slope plot (Figure D-15)
    - Slope of the straight line trend estimated an average reservoir pressure of 6533 psi
    - Higher than the calculated injecting BHP values
    - Value higher than the 4600 psi value used for the Hall integral calculation
- Tandem plot (Figure D-17)
    - Showed no correlation between the Hall integral response and cumulative earthquake trend

DFW North A1DM

- Overview plot (Figure D-10)
    - Well still currently active
    - Injection pressure constant while rate declining during 2010 and 2011
- Operating pressure gradient plot (Figure D-12)
    - Remained below the 0.7 psi/ft rule-of-thumb fracture gradient

- Hall integral and derivative plot (Figure D-14)
  - Low monthly volume suggests well did not operate continuously throughout the month, but hours operational were not reported to verify
  - Showed a negative slope break, but questionable due to data quality
    - Hall derivative remained below the Hall integral trend during period with negative slope break
- Silin slope plot (Figure D-16)
  - Slope of the straight line trend estimated an average reservoir pressure of 5206 psi
  - Higher than some the calculated injecting BHP values
  - Value higher than the 3900 psi value used for the Hall integral calculation
- Tandem plot (Figure D-18)
  - No earthquakes occurred within a 5 mile radius of the well

Actions taken by UIC regulatory agency in DFW airport study area

Following the seismic events, the RRC worked with the operator of the nearest disposal well, DFW C1DE. The operator voluntarily shut the well in, though they do not consider the evidence for induced seismicity to be conclusive. The second well, the DFW North A1DM remained operational. The RRC reviewed its permit actions for this well, as well as other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify no measurable harm or potential hazard related to the events. In follow-up, the RRC consulted with industry representatives, and researchers at the Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M University, and continues to monitor developments and research related to induced seismicity.

Cleburne Area Case Study

The Cleburne area earthquake swarm, within a five mile radius of the seven case study wells discussed below, is shown in map view on Figure D-19, and in a timeline form on Figure D-20. Expanded views of earthquake events near the case study wells are shown in Figures D-21 through D-24. A summary of the Cleburne area earthquakes recorded in the ANSS and NEIC databases is included in Table D-4. Information from the SMU portable array is being interpreted and publication is anticipated in late 2012.

TABLE D-4: CLEBURNE AREA SEISMICITY THROUGH 1/31/2012

Year	Starting Event	Number of Events	Magnitude			Ending Event
			Min.	Avg.	Max.	
2009	6/2/2009	9	2.0	2.4	2.8	10/1/2009

2010	11/8/2010	2	2.1	2.3	2.5	11/12/2010
2011		0				
2012	1/18/2012	1	3.3	3.3	3.3	1/18/2012

The following seven wells were investigated in relation to the earthquakes in 2010. All the wells are commercial disposal wells completed in the Ellenburger formation, except the Johnson County SDW 1. Permit information is summarized in Table D-5 and listed below:

Cleburne Vicinity Disposal Wells

Sparks Drive SWD 1: Class II UIC Permit 93369; Maximum permit pressure 2900 psig; 9,000 BPD; Total Depth: 9,134'; Initial Injection: December 2005; 7,509'-9,134' open-hole; Ellenburger commercial disposal.

Commented [A88]: R9 comment – two different max permit pressures are different. Recommend removing Class I permit info since discussing Class II permits.

S Mann SWD 1: UIC Permit 94931; Maximum permit pressure 3708 psig; 20,000 BPD; Total Depth: 9,071'; Recompleted and initial Injection: October 2006; 7,627-9,071' open-hole; Ellenburger commercial disposal.

South Cleburne SWD 1: UIC Permit 94930; Maximum permit pressure 3650 psig; 20,000 BPD; Total Depth: 10,952'; Initial Injection: October 2006; Final injection: July 2009; Authorized interval 7,300-10,800'; Ellenburger commercial disposal; temporarily abandoned.

Johnson Salty SWD 2: UIC Permit 96487; Maximum permit pressure 3500 psig; 30,000 BPD; Total Depth: 10,000'; Initial Injection: January 2007; 7,210-10,000'; Ellenburger commercial disposal.

Johnson Salty SWD 3: UIC Permit 96488; Maximum permit pressure 3500 psig; 30,000 BPD; Total Depth: 12,000'; Initial Injection: February 2008; 7,200-10,000'; Ellenburger commercial disposal.

Cleburne Yard 1: UIC Permit 97113; Maximum permit pressure 2300 psig; 15,000 BPD; Total Depth: 10,128'; Recompleted and initial Injection: August 2007; 7,650-11,500'; Ellenburger commercial disposal.

Johnson County SDW 1: UIC Permit 95581; Total Depth: 11,213'; Maximum permit pressure 3800 psig; 25,000 BPD; Initial Injection: January 2007; 7,995-10,821'; Ellenburger, open hole.

Commented [A89]: SWD? Commercial disposal or not?

TABLE D-5: CLEBURNE AREA DISPOSAL WELL CONSTRUCTION

Well	Total Depth	Casing Diameter and Setting Depth	Tubing Diameter and Seat	Perforations

Well	Total Depth	Casing Diameter and Setting Depth	Tubing Diameter and Seat	Perforations
Sparks Drive SWD 1 (WDW-401)	9134’	5 ½” at 7509’	3 ½” at 7421’	Open-hole 7509’ to 9134’ Fill at 7882’ in Aug 2011
S. Mann SWD 1	9071’	7” at 7627’	3 ½” at 7425’	Open-hole 7627’ to 9071’
South Cleburne SWD 1	10,952’	7” at 10,903’	4½” at 10,349’	10,422’-10,755’
Johnson Salty SWD II Well 2	9810’	7” at 9808’	4” at 6950’ Replaced w/ 4½“ at 7080’ in Mar 2011	Disposal interval 7210’ to 10,000’
Johnson Salty SWD III Well 3	9799’	7” at 9799’	4” at 7100’ Replaced w/ 4½” at 7750’ in Mar 2011	Disposal interval 7850’ to 10,000’
Cleburne Yard 1	10,128’	7” at 7850’	4 ½” at 7765’	Injection interval 7,650-11,500’
Johnson County SWD 1	11,213’	7” at 7994’	4 ½” at 7981’	Open-hole 7,995-10,821’

Additional Data Collected

The Sparks Drive SWD is dually permitted as a Class II commercial with the RRC and as the WDW-401 Class I disposal well with the Texas Commission on Environmental Quality (TCEQ). Class I wells are required to conduct annual falloff tests. In this appendix Sparks Drive SWD 1 and WDW-401 will be referred to as the Sparks Drive SWD 1. EPA acquired the 2005, 2006, and 2008 through 2011 annual falloff pressure transient tests for the Sparks Drive SWD 1. Analyses of these pressure transient tests for Sparks Drive SWD 1 are included in this case study. No pressure transient tests were available for the other wells. The wellbore schematic for the Sparks Drive SWD 1 is shown in Figure D-25.

Operational Analysis Plots and Observations

Operational data was reviewed and analyzed for all five wells. The analysis plot for each well is included in the following list of figures:

- Operational data overview plots: Figures D-26 through D-32
- Operational pressure gradient plots: Figures D-33 through D-39
- Hall integral and derivative plot: Figures D-40 through D-46
- Silin slope plots: Figures D-47 through D-53
- Tandem plots: Figures D-54 through D-60

Table D-6 summarizes data associated with the Hall integral and Silin slope plot and compares the average pressure estimated for the Hall integral to the value determined from the corresponding Silin slope plot.

TABLE D-6: CLEBURNE AREA HALL AND SILIN SLOPE PLOT RESULTS SUMMARY

Well	Assumed Average Pressure for Hall Plot (psia)	Calculated Average Pressure from Silin Slope Plot (psia)
Sparks SWD 1 (WDW-401)	3800	3875
S. Mann SWD 1	3100	4642
South Cleburne SWD 1	4730	4879
Johnson Salty SWD Well II	3200	4048
Johnson Salty SWD Well III	3600	4002
Cleburne Yard SWD 1	3530	4152
Johnson County SWD 1	3600	4301

The operating pressure data analysis completed for each well is summarized below.

- Operational data overview plots (Figures D-26 through D-32)
- Operating pressure gradient plots (Figures D-33 through D-39):
  - Below 0.7 psi/ft rule of thumb fracture gradient in all wells
- Hall integral and derivative plot:
  - Sparks SWD 1 (Figure D-40)
    - A single negative slope break on Hall integral at approximately 1.1 MMbbls (June 2007)
    - Derivative stays below Hall integral until 2.49 MMbls (April 2008)
  - S. Mann SWD 1 (Figure D-41)
    - Negative slope break on Hall integral at approximately 2.6 MMbbls (May 2007)
    - Derivative moves below Hall integral and remains below until approximately 21 MMbbls (Oct 2010)
  - South Cleburne SWD 1 (Figure D-42)
    - Negative slope break on Hall integral at approximately 3 MMbbls (June 2007)
    - Derivative moves below Hall integral and remains below through the remainder of the test
  - Johnson Salty SWD Well II (Figure D-43)
    - Normal injection behavior with some derivative scatter due to rate fluctuations
  - Johnson Salty SWD Well III (Figure D-44)

        - Normal injection behavior with some derivative scatter due to rate fluctuations
    - Cleburne Yard SWD 1 (Figure D-45)
        - Several negative slope breaks on Hall integral and derivative generally located below Hall integral after 1.16 MMbls (February 2009)
    - Johnson County SWD 1 (Figure C-46)
        - Two negative slope breaks on Hall integral at approximately 1 MMbbls (July 2007) and 12 MMbbls (July 2009)
- Silin slope plot:
    - Sparks Drive SWD 1 (Figure D-47)
    - S. Mann SWD 1 (Figure D-48)
    - South Cleburne SWD 1 (Figure D-49)
    - Johnson Salty SWD Well II (Figure D-50)
    - Johnson Salty SWD Well III (Figure D-51)
    - Cleburne Yard SWD 1 (Figure D-52)
    - Johnson County SWD 1 (Figure D-53)

The average reservoir pressures predicted by the slope plots were generally higher than the static pressure values assumed for the Hall integral plots. The difference may possibly be attributed to the well exhibiting slope breaks on the Hall plot.

- Tandem plot: (Figures D-54 through D-60)
    - Sparks Drive SWD 1 (Figure D-54)
        - No correlation observed
    - S. Mann SWD 1 (Figure D-55)
        - No correlation observed
    - South Cleburne SWD 1 (Figure D-56)
        - No correlation observed
    - Johnson Salty SWD Well II (Figure D-57)
        - Hall integral shift observed at 8.1 MMbls (May 2009) corresponding to a series of earthquake events
    - Johnson Salty SWD Well III (Figure D-58)
        - Hall integral shift observed at a cumulative injection at approximately 8.3 MMbbls (May 2009) corresponding to a series of earthquake events
    - Cleburne Yard SWD 1 (Figure D59)
        - Two series of earthquake events occur prior to two slope changes on the Hall plot
    - Johnson County SDW 1 (Figure D-60)
        - No correlation observed

Pressure Transient Test Plots and Observations

Annual falloff test data for Sparks SWD 1 was analyzed using PanSystem® welltest software. Each test was plotted in a log-log format with the derivative response and then compared against various reservoir type curve models to identify flow regimes and reservoir and completion characteristics present. Data specific to each falloff test is summarized in Table D-7.

A summary of the Sparks Drive SWD 1 pressure transient test plot analyses are summarized in Table D-8 and additional discussion on select tests is included below:

- 2005 and 2006 falloff test
    - Overview plot (Figure D-61 and D-65)
        - 2005 pressure declining measurably (1.33 psi/hr) at the end of the test
        - 2006 pressure declining measurably (1.74 psi/hr) at the end of the test
    - Log-log plot (Figure D-62 and D-66)
        - 2005 and 2006 plots suggest a highly stimulated completion followed by a pressure derivative decline
        - 2006 – linear derivative added indicating linear flow during part of the test (Figure D-67)
    - Type curve match
        - 2005 Radial homogeneous type curve (Figure D-63)
            - Suggests a stimulated completion
            - Late time data deviated from the fracture type curve model
        - 2005 and 2006 Infinite conductivity fracture type curve (Figure D-64 and D-69)
            - Suggests high conductivity fracture
            - 2006 test yielded similar match results with both infinite and finite conductivity (Figure D-68) fracture type curves
        - 2006 test could be matched using only the early (Figure D-69) or late time (Figure D-70) portions of the tests
            - Overall test did not fit a single type curve model
            - Both early and late responses fit a fracture type curve model with similar fracture half length dimensions
            - Early response kh result was roughly twice late response kh value
- 2008 Falloff test
    - Overview plot (Figure D-71)
        - Pressure declining measurably (1.26 psi/hr) at the end of the test
    - Log-log plot (Figure D-72)
        - Linear flow behavior followed by late time derivative decline

- o Type curve
    - Radial homogeneous type curve (Figure D-73)
        - Suggests a stimulated completion
    - Infinite conductivity fracture type curve (Figure D-74)
        - Highly conductive fracture with results similar to 2005 and 2006 falloff tests

- 2009 Falloff test
    - Overview plot (Figure D-75)
        - Pressure declining measurably (0.82 psi/hr) at the end of the test
    - Log-log plot (Figure D-76)
        - Late time data shows a derivative decline with a negative half slope
            - Possibly indicating spherical flow/layering
    - Dual permeability type curve (Figure D-77)
        - Late time portion of test fit a two layer model
- 2010 Falloff test
    - Overview plot (Figure D-78)
        - Pressure declining measurably (2.45 psi/hr) at the end of the test
    - Log-log plot (Figure D-79)
        - Linear flow with late time derivative decline
    - Type curve
        - Infinite conductivity fracture type curve (Figure D-80)
            - Highly conductive fracture similar to 2005, 2006 and 2009 falloff tests
        - Dual Permeability type match with late time data only (Figure D-81)
            - Late time portion of test fit a two layer model
- 2011 Falloff test
    - Overview plot (Figure D-82)
        - Pressure declining measurably (3.38 psi/hr) at the end of the test
    - Log-log plot (Figure D-83)
        - Highly stimulated completion
    - Type curve (Figure D-84)
        - Infinite conductivity fracture type curve
            - Marginal match with a highly conductive fracture similar to 2005, 2006, 2009, and 2010 tests

TABLE D-7: SPARKS DRIVE SWD 1 (WDW 401) FALLOFF TEST CONDITIONS

Test Date	Injection Time (hrs)	Shut-in Time (hrs)	Gauge Depth (ft KB)	Final Injection Pressure (psia) and Rate (gpm)	Final Shut-in Pressure (psia) and Pressure Decline Rate (psi/hr)

8/29-30/2005	30.12	18.7	7620	4189.33/ 156	3851.12 / 1.33
9/21-22/2006	16	20.5	5500	3361.79/ 173	2921.68/ 1.74
8/25-26/2008	13.17	21.25	7500	4227.07/ 215	3859.42/ 1.26
8/27-28/2009	124.2	21.18	6334	3781.70/ 128	3281/ 0.82
8/4-5/2010	18.5	20	7620	4252.49/ 95.5	3876.98/ 2.45
8/1-2/2011	240	20.2	7620	4316.90/ 99	3973.69/ 3.38

Sparks Drive SWD 1 (WDW-401) Falloff Tests Summary

Tests generally indicated a fractured or highly stimulated completion signature, but entire test responses did not fit a simple model. Early time test responses were fitted to type curve models while the late time portions of the test deviated from the type curve response.

Late time test behaviors indicated pressure support/communication in the form of a declining pressure derivative response. This could reflect communication with a pressure support source, such as another layer. Two of the late time test responses fit a dual permeability (two layer) type curve model.

Type curve matches were marginal, but all indicated a highly stimulated completion with matches obtained using both homogeneous reservoir and infinite conductivity fracture type curves to match the early portions of several falloffs. As the Ellenburger formation is naturally fractured, this type of response is consistent.

Matches also indicated a moderate transmissibility interval with transmissibilities in the 4,000-15,000 md-ft/cp range. Fracture characteristics from the type curve matches fit an unpropped fracture with fracture wing lengths on the order of 160 to 250 feet long.

The falloffs did not reach static pressure conditions at test end time as all the falloffs displayed noticeable pressure declines at their conclusions.

TABLE D-8: CLEBURNE AREA FALLOFF TEST ANALYSIS RESULTS

Test	Type Curve Model	kh/u (md-ft/cp)	Skin Factor	x_f (ft)	Comments
2005	Homogeneous	3633	-5.3	---	
	Infinite Conductivity Fracture	3287	-5.7	200	
2006	Finite Conductivity Fracture	10,380	-4.5	190	
	Infinite Conductivity Fracture	10,380	-4.5	160	Early time data match
	Infinite Conductivity Fracture	4325	-5.6	170	Late time data match

2008	Homogeneous	13,107	-5.3		
	Infinite Conductivity Fracture	12,317	-5.4	176	
2009	---	---	---	---	Not quantitatively analyzable
2010	Infinite Conductivity Fracture	2595	-5.6	175	
2011	Infinite Conductivity Fracture	4556	-5.5	254	

ACTIONS TAKEN BY UIC REGULATORY AGENCY IN THE NORTH TEXAS CLEBURNE AREA

Following the seismic events, the RRC worked with the operator of the nearest disposal well, ~~Chesapeake Operating, Inc.'s:~~ *South Cleburne SWD 1*. ~~Chesapeake~~ The operator voluntarily shut the well in, though they do not consider the evidence to be conclusive. The RRC reviewed its permit actions for this wells, as well as other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify no measurable harm or potential hazard related to the events. In follow-up, the RRC consulted with industry representatives, and researchers at the Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M University, and continues to monitor developments and research related to induced seismicity.

CITATIONS

ANSS: <http://quake.geo.berkeley.edu/cnss/>

Bruner, K. R., and Smosna, R., 2011, A comparative study of the Mississippian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin: US Department of Energy, National Energy Technology Laboratory.

Eisner, L., 2011, Seismicity of DFW, Texas, USA, National Academy of Science Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas.

Frohlich, C. et al., 2011, Dallas-Fort Worth earthquake sequence: October 2008 through May 2009: Bulletin of the Seismological Society of America, v. 101, p. 327-340.

Martineau, D. F., 2007, History of the Newark East field and the Barnett Shale as a gas reservoir: AAPG Bulletin, v. 91, no. 4, p. 399-403.

McDonnell, A. et al., 2007, Quantifying the origin and geometry of circular sag structures in northern Forth Worth Basin, Texas: Paleocave collapse, pull-apart fault systems, or hydrothermal alteration?: AAPG Bulletin, v. 91, no. 9, p. 1295-1318.

Montgomery, S. L. et al., 2005, Mississippian Barnett Shale, Fort Worth Basin, northcentral Texas: Gas-shale play with multi-trillion cubic foot potential: AAPG Bulletin, v. 89, no. 2, p. 155-175.

NEIC: <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>

Steward, D. B., 2011, The Barnett Shale oil model of North Texas, Article #110151, Search and Discovery, American Association of Petroleum Geologists/Datapages, Inc.

APPENDIX E: CENTRAL ARKANSAS AREA CASE STUDY

BACKGROUND

From 2009 through 2011 a series of minor earthquakes occurred near the towns of Guy and Greenbrier in Faulkner County, Arkansas. The news media initially attributed these quakes to hydraulic fracturing in the Fayetteville Shale unconventional gas play illustrate on (Figure E-1). Through deployment of additional seismographs, discussions with the various oil and gas operators, and coordination between the Arkansas Oil and Gas Commission (AOGC), Arkansas Geologic Survey (AGS) and Center for Earthquake Research and information (CERI) at the University of Memphis, a more detailed picture emerged.

HISTORY OF SEISMICITY

In 1811 and 1812, a series of magnitude 7 earthquakes rocked the New Madrid Seismic Zone (NMSZ), (USGS, 2011a). In 1982, Arkansas experienced the Enola swarm of earthquakes with the largest magnitude of 4.7 (USGS, 2011b) as shown on the timeline in Figure E-2. The more recent Greenbrier area earthquakes were located nine miles from the edge of the Enola swarm and approximately 100 miles from the edge of the NMSZ as illustrated in Figure E-1. Additional seismometers, illustrated in Figure E-3, were deployed to investigate the Greenbrier area earthquakes. Detailed information about the Greenbrier area earthquakes is available from the publication by Steve Horton with CERI (Horton and Ausbrooks, 2011), and the AOGC 180A-2011-07 hearing Exhibits by Scott Ausbrooks with AGS (Ausbrooks, 2011a, 2011b, 2011c, 2011d) and Steve Horton (Horton, 2011).

A summary of the recent Greenbrier area earthquakes recorded in the ANSS, NEIC, and CERI catalogs, within a five mile radius of the case study wells discussed below, is provided in Table E-1 below and a timeline of events is shown on Figure E-4. A zoomed map area of the disposal well and earthquake activity is included on Figure E-5. According to the AGS, both the Enola and Guy-Greenbrier focal mechanisms reveals a fault oriented N22°E (AGS, personal communication, September 15, 2011).

TABLE E-1: GREENBRIER AREA SEISMICITY THROUGH 1/31/2012

Year	Starting Date	Number of Events	Magnitude			Ending Date
			Min.	Avg.	Max.	
1982	1/18/1982	36	1.9	3.1	4.3	11/21/1982
1983	1/19/1983	9	1.8	2.5	3.5	7/12/1983
1984	7/12/1984	8	1.5	2.3	3.2	11/12/1984
1985	2/24/1985	24	1.3	2.1	3.3	12/24/1985
1986	1/5/1986	18	1.3	2.0	3.0	11/8/1986
1987	2/23/1987	10	1.2	2.1	2.9	12/20/1987
1988	1/2/1988	7	1.0	1.7	2.2	4/21/1988
1989	4/1/1989	3	1.5	1.9	2.2	4/6/1989
1990	8/17/1990	6	1.8	2.1	2.6	12/10/1990
2001	5/4/2001	4	2.7	3.2	4.3	5/5/2001
2002		0				
2003	12/14/2003	2	2.7	2.8	2.8	12/15/2003
2004		0				
2005	1/27/2005	1	2.7	2.7	2.7	1/27/2005
2006	4/9/2006	2	2.8	2.8	2.8	10/17/2006
		0				
2009	10/15/2009	7	2.4	2.7	3.0	10/31/2009
2010	2/18/2010	677	0.2	1.8	4.4	12/31/2010
2011	1/1/2011	732	1.0	2.2	4.7	12/22/2011
2012	1/14/2012	2	2.0	2.1	2.2	1/14/2012

Five mile radial areas around each case study well are shown in Figures E-8, E-10, E-12, and E-14. The corresponding seismicity timelines of events associated with each well are shown in Figures E-9, E-11, E-13, and E-15.

GEOLOGIC SETTING

The Greenbrier area is located in the Arkansas valley region of the eastern Arkoma basin. There are at least three phases of faulting as shown on the East Arkoma Basin structural cross-section in Figure E-6. The most recent, normal listric faults sole out on the Mississippian-Pennsylvanian unconformity. The steep deeper normal faults extend into the basement faults (Van Arsdale and Schweig, 1990). Not shown, is the recently discovered Guy-Greenbrier fault[27] that appears to be a fairly vertical, normal fault cutting on the north end from the basement up to the upper Mississippian-Pennsylvanian unconformity (Horton and Ausbrooks, 2011; ~~Chesapeake Energy,~~ P~~p~~erson communication, September 16, 2011).

The Paleozoic section contains alternating carbonates, shales, and sandstones overlying crystalline basement rock. As illustrated in the stratigraphic column in Figure E-7, the Ozark confining unit separating the Boone and Hunton formations from the Ozark Aquifer[28] is thin or missing in the study area. The lower Ozark confining unit separating the Arbuckle from the Cambrian St. Francis Aquifer group and basement rock at the north end of the profile is also missing in this area.

Commented [A90]: Van Arsdale cmt

Commented [A91]: Van Arsdale cmt

Oil and Gas Activity

The central portion of the Fayetteville Shale gas play started in 2004 and covers parts of Cleburne, Conway, Faulkner, Independence, Pope, Van Buren and White counties. Fayetteville shale production wells are typically horizontally completed with laterals from 4,000' to 7000' in length at depths between 2,000' and 6,000'.

Vicinity Disposal Wells

For the reservoir engineering analysis of this case study, EPA focused on four area disposal wells: E.W. Moore Estate 1-22, Wayne L. Edgmon 1, Trammel 7-13 1-8D, and SRE 8-12 1-17 SWD. Data were gathered from the permit applications and operational history for each well. Table E-2 provides a summary of each well's construction and completion information. Figures E-16 through E-18 are wellbore schematics of the Moore, Edgmon, and Trammel wells. No wellbore schematic was included for the SRE well. Additional details for each well are summarized below:

E W Moore Estate 1-22 SWD: Permit No. 39487; Commercial well; Maximum permitted pressure of 3,000 psig and rate of 6,000 BPD; Total Depth: 10,600'; Initial injection Jun 1, 2009; Final injection: Jul 15, 2011; Authorized injection zone 7,760'-10,600'; Injection formations - Boone through Arbuckle; plugged and abandoned Sep 29, 2011.

[27] Note that the precise location and upper elevation depend on the particular velocity model used, and vary between the two sources of information.

[28] The Ozark Aquifer is not a USDW in this area.

Wayne L Edgmon (1) SWD: Permit No. 36380 Commercial well; Maximum permitted pressure of 8454 psig and rate of 20,000 BPD; Total Depth: 12,163'; Authorized initial Injection Aug 18, 2010; Final injection Mar 14, 2011; Authorized formation - Arbuckle; temporarily abandoned. This well was originally drilled as an exploratory well into Precambrian crystalline basement.

Trammel 7-13 1-8D SWD: Permit No. 41079; Maximum permitted pressure of 2300 psig and rate of 12,000 BPD; Total depth: 7,160'; Authorized initial injection April 2009; Final injection June 2011; Authorized injection zone 6,503'-6,590'; Injection formation - Boone; plugged and abandoned Oct 19, 2011.

SRE 8-12 1-17 SWD: Permit No. 43266; Maximum permitted pressure of 3330 psig and rate of 20,000 BPD; Total Depth: 6,500'; Initial injection Jul 8, 2010; Final injection Mar 2011; Authorized injection zone 5,992'-6,277'; Injection formations - Boone and Hunton; plugged and abandoned Sep 30, 2011.

TABLE E-2: GREENBRIER AREA WELL CONSTRUCTION INFORMATION SUMMARY

Well	Total Depth	Casing Diameter and Seat	Tubing Diameter and Seat	Completed Interval
E.W. Moore Estate 1-22	10600'	5 ½" to 8087'	2 7/8" to 8077'	Open-hole below 8087'
Wayne Edgmon 1	12163'	4 ½" to 12162'	2 7/8" to 7710'	7806'-10970'
Trammel 7-13 1-8D	7160'	5 ½" to 7126'	3 ½" to 6800'	6836'-6936'
SRE 8-12 1-17 SWD	6500'	7" to 6500'	4 ½" to 5925'	6044'-6312'

Commented [A92]: (listed numbers were from well proposal)
Approved: 5992-6107 Boone 6132-6277 Hunton
Perfed: 6044-6128 & 6216-6312

Data Collected

Data for these four wells were collected from AOGC via their website and from the state regulatory hearing documentation associated with the disposal well moratorium ruling, discussed later. Permitting documents provided details concerning completion depths, construction information, and permit conditions. Operational monitoring reports provided several months of injection rates and wellhead pressures with data being recorded as often as every hour in some wells.

Commented [A93]: Need to clarify the moratorium area somewhere in this appendix. Possibly just reference a picture…?

Data Reviewed

Data were divided into two areas: operational and pressure transient testing. All four wells had operational data for analysis. A step rate test was available for the Edgmon. Transient testing data consisted of surface pressure falloff tests embedded in the monitored pressure data for the Edgmon, SRE, and Trammel wells. Injection rates fluctuated significantly in all three wells preceding the falloffs. The pressures were recorded at the surface so no useful pressures were available after a well went on a vacuum during a shut-in period, making the falloff pressure responses of limited duration.

Operational data consisted of monthly, bi-hourly, and hourly wellhead pressures and injection volumes. The high data recording rate yielded fairly noisy data sets for operational analysis, with Edgmon data being especially noisy, but the added frequency provided sufficient data for a limited falloff test analysis during some of the shut-in periods.

Surface pressures were converted to approximate bottomhole pressures (BHP) at the tubing seat depth of each well. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A brine specific gravity of 1.025 was used based on permitting documentation for the SRE well.

Operational Analysis Plots and Observations

The operational rate and pressure data overview plot for the four case study wells is included in Figures E-19 through E-22. Pressure gradient plots (Figures E-23 through E-26), Hall integral and derivative plots (Figures E-27 through E-31), Silin slope plots (Figures E-32 through E-34) were also prepared and are discussed below.

Table E-3 summarizes the assumed reservoir pressure value used for each Hall plot and comparison with the average pressure value determined from the corresponding slope plot.

Table E-3: Comparison of Assumed Hall Plot Average Pressure Values and Slope Plot - Determined Average Reservoir Pressures

Well	Hall Plot Assumed Pressure (psia)	Slope Plot-Determined Pressures (psia)
E.W. Moore Estate 1-22	3500	6258
Trammel 7-13 1-8D	3800	4216
SRE 8-12 1-17 SWD	2400	3504

The Arkansas case study had a large number of low to moderate level earthquake events recorded, making it possible to plot a well established cumulative event trend. To determine if the earthquake cumulative event trend followed the Hall integral trend, tandem plots of cumulative earthquake events and Hall integral response versus cumulative water injection were prepared for the Moore, SRE, and Trammel wells and are shown in Figures E-35 through E-37. The Edgmon operating data was intermittent, resulting in an unstable Hall integral trend and excluded from this report.

The operating pressure data analysis completed for each well is summarized below. The results of the tandem plots are also included. Because of the location of the well from the Guy-Greenbrier fault, a tandem plot was not prepared for the E.W. Moore Estate 1-22 disposal well.

The operating pressure data analysis completed for each well is summarized below:

- Operational data overview plots (Figures E-19 through E-22)
  - E.W. Moore Estate 1-22 (Figure E-19)
    - Pressures did not fluctuate with rate changes
  - Wayne Edgmon 1 (Figure E-20)
    - Operated intermittently with significant rate fluctuations
    - Falloff test recorded during final well shut-in from more frequent surface pressure measurements during enhanced monitoring
  - Trammel 7-13 1-8D (Figure E-21)
    - Rates dipped between January and June 2010 with limited pressure decline
  - SRE 8-12 1-17 (Figure E-22)
    - Operated intermittently with significant rate fluctuations
    - Short falloff test during final well shut-in
      - Well went on vacuum so surface pressure data no longer useful for falloff test analysis
- Operating pressure gradient plots (Figures E-23 through E-26)
  - Rule of thumb pressure gradient was not used because of higher fracture gradient determined for this area
  - Highest operating gradients in the Moore well (Figure E-23)
- Hall integral and derivative plot (Figures E-27 through E-30)
  - E.W. Moore Estate 1-22 (Figure E-27)
    - Zoomed plot showed a subtle negative slope break during its first 50,000 bbls of injection (Figure E-28)
      - Derivative trend generally below Hall integral with some scatter
  - Wayne Edgmon 1
    - No Hall plot generated - small diameter tubing size coupled with intermittent disposal data resulting in an unstable Hall integral trend
  - Trammel 7-13 1-8D (Figure E-29)
    - Hall integral by itself shows both positive and negative slope changes
    - Hall derivative noisy
  - SRE 8-12 1-17 SWD (Figure E-30)
    - Normal injection behavior except for two early slope breaks
    - Zoomed Hall plot (Figure E-31) showed negative slope breaks at approximately 440,000 (8/28/2010) and 900,000 (10/6/2010) cumulative bbls
- Silin slope plot (Figures E-32 through E-34)

    - E.W. Moore Estate 1-22 (Figure E-32)
    - Wayne Edgmon 1
        - No slope plot due intermittent disposal data
    - Trammel 7-13 1-8D (Figure E-33)
    - SRE 8-12 1-17 SWD (Figure E-34)
- Tandem plot: (Figures E-35 through E-37)
    - E.W. Moore Estate 1-22 (Figure E-35)
    - Wayne Edgmon 1
        - No tandem plot
    - Trammel 7-13 1-8D (Figure E-36)
    - SRE 8-12 1-17 SWD (Figure E-37)

Pressure Transient Test Plots and Observations

Wayne Edgmon 1 Step rate test (Figure E-38)

The WG reviewed the step rate test conducted in the Edgmon and found conflict between the reported data and field notes as summarized in Tables E-4 and E-5. The data from the recorded data and field notes in Table E-5 were used for preparation of the linear plot. A drastically reduced pressure response occurred during rate step 6. The small diameter tubing size in the well coupled with high injection rate values resulted in the calculated bottomhole pressures dropping below the actual measured surface pressures due to severe calculated friction loss as shown in Figure E-38. No slope breaks were observed in the surface pressure data. The test was not considered suitable for quantitative analysis.

TABLE E-4: CLARITA OPERATING WAYNE L. EDGMON STEP RATE TEST (4/10/10).[*]

Step	Injection Rate (BPM)	Injection Rate (BWPD)	Surface Injection Pressure (psig)	Frictional Pressure (psig)	Estimated Hydrostatic Pressure (psig)	Estimated BHP Pressure (psig)
1	5.9	8500	760	710	3465	3515
2	7.0	10100	1204	1134	3465	3535
3	8.4	12100	1704	1584	3465	3585
4	9.9	14200	2380	2125	3465	3695
5	11.2	16100	3015	2715	3465	3765
6	14.4	20800	4960	4360	3465	4065
7	17.4	25000	6882	6097	3465	4250

* Edgmon data summary table in report listed inconsistent time increments and injection rates compared to the data from the recording instruments and field notes included in the report. Time increments = 15 minutes; water weight = 8.55 ppg; water specific gravity = 1.025; depth to top perforation = 7806 feet.

TABLE E-5: CLARITA OPERATING WAYNE L. EDGMON STEP RATE TEST (4/10/10).*

Step	Rate from data (bpm)	Rate (gpm)	Surface Pressure (psig)	Bottomhole Pressure (psig)	Friction Pressure (psi)	Bottomhole Pressure Corrected for Friction (psig)	Time Increments (min)
1	5.8	243.6	760	4182	1200	2982	60
2	6.9	289.8	1204	4626	1655	2971	60
3	8.3	348.6	1675	5097	2329	2768	60
4	9.9	415.8	2380	5802	2337	2575	60
5	11.1	466.2	3015	6437	3988	2449	60
6	11.2	470.4	1090	4512	4055	457	60
7	14.8	621.6	4997	8419	6791	1628	180

* Edgmon summary table compiled from recorded data and field notes. Pressure dropped during rate step 6; report provided no explanation for pressure decrease.

Surface pressure falloff test data were also reviewed for the Edgmon, Trammel and SRE, and Trammel wells using PanSystem® welltest analysis software. The final falloff periods were analyzed and the reservoir characteristics are illustrated in Figures E-39 through E-43 for the three disposal wells located closest to the Guy-Greenbrier fault. The pressure transient analysis of the step rate test for the Edgmon and the final falloff tests for each of the three wells are summarized below:

- Wayne Edgmon 1 Step rate test (Figure E-38)
    - Linear plot of surface pressure test data converted to bottomhole
        - Anomalous behavior observed during step 6
            - At a constant injection rate of 11.2 bpm
            - Surface injection pressure fluctuated greatly
                - Start at approximately 2860 psi for 5 min
                - Drop abruptly to approximately 960 psi
                - Climb gradually to approximately 1090 psi
        - Calculated BHPs declined with increasing injection rates (friction factor of 150)
            - Friction factor of 140 resulted in a negative bottomhole pressure for the final rate step so used 150
- Wayne Edgmon 1 Final falloff
    - Log-log plot analyzed using an equivalent time function (Figure E-39)
        - Time function accounts for rate history
        - Response was dominated by wellbore storage

        - Pressure derivative response exceeded the pressure change
        - Test using an equivalent time function was deemed unanalyzable
- Trammel 7-13 1-8D Final falloff test (Figures E-40 and E-41)
    - Overview plot of shut-in periods and final falloff (Figure E-40)
    - Log-log plot indicated a fracture or highly stimulated completion signature (Figure E-41)
        - Completely dominated by linear flow
        - Could not be type curve matched
- SRE 8-12 1-17 final falloff test (Figures E-42 and E-43)
    - Overview plot of shut-in periods and final falloff (Figure E-42)
    - Log-log plot indicated a fracture or highly stimulated completion signature
        - Matched using an infinite conductivity fracture model (Figure E-43)
        - Indicated a long fracture half length (> 500 feet) for this well's completion
        - Late test time derivative response indicated some pressure support present

ACTIONS TAKEN BY UIC REGULATORY AGENCY IN CENTRAL ARKANSAS AREA

Initial response was deployment of additional seismometers to better record the actual event epicenters (surface location) and focus location (depth). This was done through the combined efforts of Arkansas Geological Survey (AGS) and University of Memphis Center for Earthquake Research and Information (CERI), with some of the monitor stations directly linked into the USGS National Earthquake Information Center.

Following initial identification of the Guy-Greenbrier fault, the Arkansas Oil and Gas Commission (AOGC) established a moratorium on the drilling of any new Class II disposal wells in an area surrounding and in the immediate vicinity of the seismic activity in December 2010; and required the operators of the seven existing Class II disposal wells operating in the moratorium area to provide bi-hourly injection rates and pressures for a period of 6 months, thru July 2011. During the moratorium period AGS and CERI analyzed the injection data and seismic activity to determine if there was a relationship. The injection-induced seismicity project considered the five deeper wells closest to the Guy-Greenbrier fault selecting the three wells closest to the fault for further analysis.

Using (Wells and Coopersmith, 1994) equations, from the estimated fault rupture length and area, the potential maximum (moment) magnitude the fault in Figure E-5 could produce was estimated to be between 5.6 and 6.0. (Horton, 2011)

In February 2011, following a series of larger magnitude earthquakes, (4.7 with damage reported), the operators of the three disposal wells nearest the seismic activity voluntarily agreed to shut-in the subject disposal wells prior to the issuance of an AOGC cessation order. AOGC issued a cessation order on March 4, 2011 requiring the subject wells to cease disposal operations. In July 2011, following the conclusion of the moratorium study, AOGC established a revised permanent moratorium area in which no further Class II disposal wells could be drilled and that four of the original seven disposals wells included in the original moratorium area were required to be plugged. The revised moratorium area was based on the trend of the fault identified as the cause of the seismic activity. The operators of three of the wells (SRE, Trammel and Edgmon) voluntarily agreed to plug the subject disposal wells. The operator of the fourth disposal well (Moore) was ordered to do so following the July 2011 Commission Hearing. Three of the disposal wells (SRE, Trammel, and Moore) have been plugged by the operators, as of the date of this report. (Note: the operator of the Edgmon disposal well is in bankruptcy and the well will probably be plugged by the Commission in spring 2012 under the Commission Abandoned and Orphaned Well Plugging Program).

AOGC finalized amendments to their Class II disposal well rules effective in February 2012. These additional requirements, dealing with seismic issues, only affected disposal wells in the Fayetteville Shale development area. In addition AOGC is studying the feasibility of establishing a permanent seismic array in the Fayetteville Shale development area to monitor future disposal well operations, thereby creating a potential "early warning" system to developing seismic activity and possibly allowing sufficient time to develop adequate management strategies.

CITATIONS

ANSS: <http://quake.geo.berkeley.edu/cnss/>

Ausbrooks, S. M., 2011a, Exhibit 23: Geologic overview of north-central Arkansas and the Enola and Guy-Greenbrier earthquake swarm areas, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011b Exhibit 24: Overview of the E. W. Moore Estate No. 1 well (Deep Six SWD) and small aperture seismic array, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011c, Exhibit 25: Clarita Operating, LLC, Wayne Edgmon SWD data, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011d, Exhibit 30: Docket 063-2008-01, initial Deep Six permit hearing, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Horton, S., 2011, Exhibit 22: Central Arkansas earthquake activity: Draft of testimony to Arkansas Oil and Gas Commission, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Horton, S., and Ausbrooks, S., 2011, Earthquakes in central Arkansas triggered by fluid injection at Class 2 UIC wells, National Academy of Science Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas.

NEIC: <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>

USGS, 2011a, New Madrid 1811-1812 earthquakes, US Geological Survey, Accessed November 22 <http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php>, Last updated May 24, 2011.

USGS, 2011b, Poster of the 2010-2011 Arkansas Earthquake Swarm, US Geological Survey, <http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2011/20110228.php>.

Van Arsdale, R. B., and Schweig, E. S., 1990, Subsurface structure of the eastern Arkoma Basin: AAPG Bulletin, v. 74, p. 1030-1037.

Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

APPENDIX F: Braxton County, West Virginia, Case Study Area

Background

In 2010, a series of earthquakes occurred in Braxton County, West Virginia, (Figure F-1). The relationship between the earthquakes and a nearby Class II disposal well was investigated by the West Virginia Department of Environmental Protection Office of Oil and Gas.

History of Seismicity

Only one low level earthquake in 2000 was recorded in the ANSS database, prior to the events starting in 2010. All six seismicity databases, (ANSS, SRA, NCEER, USHIS, CERI and PDE), were searched. A summary of the recent Braxton County earthquakes, within a twelve mile area[29] of the case study well discussed below, is provided in the Table F-1 below and a timeline of events is shown on Figure F-2. A zoomed map area of the disposal well and earthquake activity is included on Figure F-3.

TABLE F-1: BRAXTON AREA SEISMICITY THROUGH 1/31/2012

Year	Starting Date	Number of Events	Magnitude			Ending Date
			Min.	Avg.	Max.	
2000	10/16/2000	1	2.5	2.5	2.5	10/16/2000
2010	4/4/2010	8	2.2	2.6	3.4	7/25/2010
2011		0				
2012	1/10/2012	1	2.8	2.8	2.8	1/10/2012

[29] The search area was increased owing to the lack of location certainty, occasioned by the poor density of seismometers.

Geologic Setting

Braxton County is located in the Appalachian basin, on the eastern edge of the Paleozoic Marcellus shale and Devonian Trenton limestone gas plays, (Figure F-1). The Marcellus outcrops in eastern West Virginia, though this is not shown in Figure F-1 (Avary, 2011).

The Marcellus unconformably overlies the Onondaga Limestone (Figures F-4, Avary, 2011 and F-5, WVGES, 2011), which is an easily recognizable marker on logs and seismic surveys. The Marcellus is predominantly siliceous, with mixed muscovite and illite, and minor amounts of pyrite and kaolinite (Boyce and Carr, 2009).

Oil and Gas Activity

Gas production in the Marcellus Shale of West Virginia started in 2005, with Braxton County drilling starting in 2006. The Elk Valley Land Corp 626407 Class II brine disposal well was initially completed in the Marcellus shale as a gas production well. The vertical well was later converted to disposal into the same interval.

Vicinity Disposal Wells

Only one disposal well is currently permitted to inject into the Marcellus in the state and was the focus of this case study. Injection activities began in the Elk Valley Land Corp SWD in March 2009 about one year prior to the start of seismic events. A zoomed map area of the disposal well and earthquake activity in Braxton County is included on Figure F-3. Figure F-6 is a wellbore schematic illustrating the construction and completion information for the Elk Valley Land Corp Well No. 626407. Additional details are summarized below:

Elk Valley Land Corp 626407; UIC Permit 2D0072539; Completed 08/07/2007; Initial injection March 2009; Authorized injection zone 6,472’-6,524’; Marcellus.

Data Collected

The West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas provided the permitting and operational data used in analysis of the Elk Valley Land Corp SWD. Annual report data included monthly injection volumes, maximum injecting tubing pressure, maximum shut-in tubing pressure, and hours operated during the month. Permit information indicated that the vertical well was initially fractured with a total of 355,000 pounds of sand and 14,398 barrels of water prior to being converted to a disposal well.

Permit application data provided tubing dimensions and depth (2 7/8”, 6.5 lb/ft, at 6395’, inner diameter 2.441”). The chlorides in the fluid analysis included in the permitting documentation ranged from 0-250,000 mg/L.

A step rate test was performed on the Elk Valley Land Corp SWD in March 2008, prior to injection, and was also included with the permit information. The injection rate started at 0.5 and increased to 5.5 barrels per minute over eight rate steps. Individual steps were primarily 30 minute intervals, except for the last step held for 3 hours. A total of 1,410 barrels was injected into the well during 6.5 hours of step rate testing. A summary of the rate and tubing pressure measurements is included in Table F-2.

DATA REVIEWED

Monthly data included hours operated which was used to convert the monthly injection volume to an average injection rate. The operating surface pressure was the average of the maximum injection and maximum shut-in pressures for each month. Surface pressures were converted to approximate bottomhole pressures (BHP) at 6395 feet. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 100 for steel tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A brine specific gravity of 1.125 was used to approximate 100,000 ppm chloride brine. The hydrostatic column of fluid was calculated at 3115 psia. Because the well went on a vacuum an average static reservoir pressure of 2800 psia was assumed for the Hall integral calculation. Four operating data-related plots were prepared including operational overview data plot, operating gradient plot, a Hall integral and derivative plot based on average tubing pressure, and a Silin slope plot.

TABLE F-2: STEP RATE TEST DATA

Injection Tubing Pressure at the End of Each Rate Step (psig)	Average Constant Injection Rate for Rate Step (bbls/min)
150	0.5
-235	1.0
-220	1.5
-120	2.0
400	3.0
1160	4.0
1750	5.0
1900	5.5

Figure F-7 contains an overview plot of the operational data used in the analysis. Figure F-8 is a plot of the calculated operating bottomhole pressure gradient.

The monthly hours reported indicated that the well did not operate continually throughout the month. The Hall integral and derivative functions are continuous functions from monthly data using only the hours operated in month for calculation of the functions. For the Hall integral calculations, a static pressure of 2800 psia was assumed, slightly below the calculated hydrostatic BHP. Figure F-9 is a plot of the Hall integral and derivative trend for the disposal well and Figure F-10 contains the Silin slope plot. A cumulative look at the data is provided in the tandem plot in Figure F-11.

Operational Analysis Plots and Observations

Operating Pressure Gradient (Figure F-8)

- Remained below 0.7 psi/ft
  - Lower value than the break pressure gradient in the step rate plot

Hall Plot and Derivative (Figure F-9)

- Used an average reservoir pressure of 2800 psi
- Indicated negative slope breaks
  - Negative slope breaks suggest injection enhancement or fracturing
- Hall derivative separates below the Hall integral function at each of the slope breaks
  - Representative of a fracturing response

Silin Slope Plot (Figure F-10)

- Slope of the straight line trend on the Silin slope plot estimated an average reservoir pressure of 3324 psi
  - Higher than some of the calculated injecting BHP values
  - Value higher than the 2800 psi value used for the Hall integral calculation

Tandem Plots

- Hall integral and cumulative earthquake events were plotted on the same graph with a common x axis (Figure F-11)
  - Limited cumulative earthquake count
  - Showed fracture signature prior to earthquake count
- Seismicity timeline (Figure F-2)
  - No correlation in events observed

A linear plot of the step rate test data was plotted and shown in Figure F-12. The linear plot is the final injection pressure at the end of each rate step versus the injection rate for that step. EPA was unable to obtain any electronic data of the step rate test so no log-log plot of each individual injectivity test could be analyzed. The well went on a vacuum following the first rate step. Pressures increased to nearly 2000 psi after positive pressures were reestablished during the 5th rate step.

Step Rate Test (Figure F-12)

- Linear plot indicated a slope break between the 6th and 7th rate steps of 4 and 5 barrels per minute
    - Suggesting a fracture extension surface pressure of roughly 1700 psi
        - Value would suggest a fracture gradient on the order of 0.7 psi/foot

Although the Hall plot showed several slope breaks, the calculated operating gradient showed operating gradients below 0.7 psi/foot, below the fracture extension gradient indicated by the step rate test linear plot.

Actions taken by UIC regulatory agency in Braxton County, WV area

In response to the seismic activity starting in April 2010, the West Virginia Department of Environmental Protection Office of Oil and Gas (WVDEP) reduced the injection rate in the Elk Valley Land Corp SWD. Because of the January 2012 event, the WVDEP restricted both the volume and rate into the well versus just the rate in an effort to further minimize seismic events.

Citations

ANSS: <http://quake.geo.berkeley.edu/cnss/>

Avary, K. L., 2011, Overview of gas and oil resources in West Virginia, West Virginia Geological & Economic Survey.

Boyce, M. L., and Carr, T. R., 2009, Lithostratigraphy and petrophysics of the Devonian Marcellus interval in West Virginia and southwestern Pennsylvania: Morgantown, West Virginia University, p. 25.

APPENDIX G: YOUNGSTOWN, OHIO CASE STUDY

BACKGROUND

On March 17, 2011, a series of low magnitude earthquakes began in Mahoning County in and around Youngstown, Ohio, (Figure G-1). A nearby commercial Class II disposal well, Northstar 1, was shut in by the Ohio Department of Natural Resources (ODNR) following a 4.3 magnitude earthquake on December 31, 2011. According to the *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area* published in March 2012 by the ODNR, data suggests seismicity was related to Class II disposal. The Northstar 1 was drilled 200 feet into the Precambrian basement rock. The ODNR report also suggests that pressure from disposal activities may have communicated with a critically stressed fault located in the Precambrian basement rock.

HISTORY OF SEISMICITY

Historically, there had been no prior seismicity recorded in the (county?), based on a search of the six seismicity databases, (ANSS, SRA, NCEER, USHIS, CERI and PDE). Table G-1 is based on the ANSS catalog and the Ohio Seismic Network and summarizes events occurring within a six mile radius of the North Star 1 case study well. A timeline of events is shown on Figure G-2. A zoomed map area of the disposal well and earthquake activity is included on Figure G-3.

TABLE G-1: YOUNGSTOWN AREA SEISMICITY THROUGH 1/31/2012

Year	Starting Date	Number of Events	Min.	Avg.	Max.	Ending Date
2011	3/17/2011	11	2.1	2.5	4.3	12/31/2011
2012	1/13/2012	1	2.1	2.1	2.1	1/13/2012

Geologic Setting

Youngstown is located in Mahoning County near the border of Pennsylvania, on the western flank of the Appalachian Basin. Figure G-4, (Baranoski, 2002; ODNR) illustrates the general structure across Ohio with deep Precambrian structures overlain by Paleozoic beds thickening to the east into the Appalachian Basin. Figure G-5, (ODNR, 2004) shows the stratigraphic column for eastern Ohio.

Oil and gas activity is plentiful in the area, with production from the upper Devonian Berea, and lower Silurian sandstones. The Cambrian Knox unconformity, rarely penetrated, marks the top of the injection interval permitted in the Youngstown area. To ensure complete penetration of the Mount Simon Sandstone, all of the wells were drilled into the Precambrian. ODNR indicates that the North Star 1 encountered primarily biotite, quartz, amphibole, and feldspar with undetermined trace minerals for the first 80 feet of Precambrian before reaching granite. There were indications of high angle fractures around the contact between the two rock types.

Very little control is available for the basement Precambrian structure, but regional maps based on well control combined with seismic lines and other control have been compiled, (Baranoski, 2002; ODNR, Pennsylvania Geological Survey, OFGG-05). Inclusion of the new well information with the published Precambrian maps supports the lack of additional faulting in the area around Youngstown.

Vicinity Disposal Wells

Six North Star disposal wells have been permitted for injection, in the Youngstown area. According to the ODNR only one has injected, though five have been drilled and completed. All of them are completed from the Knox into the Precambrian.

Injection activities began in the North Star 1 in December 2010 about three months prior to the start of seismic events. A zoomed map area of the disposal well and earthquake activity in Mahoning County is included on Figure G-3. Figure G-6 is a wellbore schematic illustrating the construction and completion information for the North Star 1 summarized below:

North Star 1 (SWIW 10); UIC Permit 3127; Completed 05/13/2010; Initial injection 12/22/10; open-hole completed interval 8,215’-9,180’, top Knox through 200’ of Precambrian. Acidized 8/2/2011.

Data Collected

The ODNR through the Oil and Gas Resources Division collected and provided the WG with the permitting, operational data, fluid analysis, and step rate test used to evaluate the Northstar 1. Data provided by the Agency included daily injection volumes, daily hours operation, and wellhead injection pressures. Permit application and completion data provided tubing dimensions and depth (3 1/2” at an approximate depth of 8215’ with an inner diameter assumed of 2.875”). The fluid analysis indicated a specific gravity of 1.03. Two increases in the maximum allowable surface pressure were authorized by ODNR based on the specific gravity of the injectate.

DATA REVIEWED

The available operational data was reviewed. The operating surface pressure was based on the final daily injection pressure value reported. Surface pressures were converted to bottomhole pressures (BHP) at 8215 feet. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by adding the measured surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A brine specific gravity of 1.03 was used based on the fluid analysis provided in the permit application. The hydrostatic column of fluid was calculated at 3662 psia. An initial bottomhole pressure of 3803 psi was used based on the initial pressure measured in Northstar 4. Five operating data-related plots (Figures G-7 through G-11) were prepared including an operational overview data plot, an operating gradient plot, a Hall integral and derivative plot based on average tubing pressure, Silin slope plot, and a tandem plot. The June 2010 step rate test conducted to evaluate the injectivity into the well was also reviewed (Figure G-12).

Figure G-7 contains an overview plot of the operational data used in the analysis. Figure G-8 is a plot of the calculated operating pressure gradient. The monthly hours reported indicated that the well did not operate continually throughout the month. The Hall integral and derivative functions were plotted as continuous functions from monthly data using only the hours operated in month for calculation of the functions. For the Hall integral calculations, a static pressure of 3803 psia was assumed, based on the static bottomhole pressure measurement in Northstar 4. Figure G-9 is a plot of the Hall integral and derivative trend for the disposal well and Figure G-10 contains the Silin slope plot. A cumulative look at the data is provided in the tandem plot in Figure G-11. The step rate test is illustrated in Figure G-12.

OPERATIONAL ANALYSIS PLOTS AND OBSERVATIONS

Overview Plot (Figure G-7)

- Higher injection rates followed acid stimulation

Operating Pressure Gradient (Figure G-8)

- Plateau at 0.75 psi/ft bottomhole operating gradient for extended time frame
    - 0.75 psi/ft was basis for determining maximum surface pressure limit in permit

Hall Plot and Derivative (Figure G-9)

- Used an average reservoir pressure of 3803 psi
- Indicated negative slope break
  - Negative slope break suggest injection enhancement or more interval accepting fluid
- Hall derivative stays below the Hall integral function after early initial slope break

Silin Slope Plot (Figure G-10)

- Slope of the straight line trend on the Silin slope plot estimated an average reservoir pressure of 5349 psi
  - Value much higher than the 3803 psi value used for the Hall integral calculation based on the measure static bottomhole pressure in the Northstar 4

Tandem Plot (Figure G-11)

- Hall integral, Hall derivative, and cumulative earthquake events were plotted on the same graph with a common x axis
  - Limited cumulative earthquake count
  - Earthquakes began after initial slope break
- Seismicity timeline (Figure G-2)

Step Rate Test (Figure G-12)

- Designed as an injectivity test to evaluate the formation's ability to accept fluid
- Test conducted through 5.5" production casing
- Pressure fluctuations measured during some of the rate steps
- Full range of pressure gauge (10,000 – 15,000 psi) excessive for measured pressure range (1800 psi maximum)
- Unable to determine from the step rate tests report if the pressure was stabilized during each rate step
- Slope breaks
  - Several different straight lines could be drawn suggesting breaks after steps 2, 5, and 6
  - Final slope is nearly flat between steps 7 and 8

Actions taken by UIC regulatory agency in the Youngstown, Ohio area

Commented [A94]: Confirm with ODNR and Ohio EPA that this reflects latest information.

Following a 4.3 magnitude earthquake (ANSS) on December 31, 2011, ODNR shut in the Northstar 1 pending further evaluation. The ODNR revised regulations prohibit Class II injection into the Precambrian basement rock and adopted additional standard permit requirements to facilitate better site assessment and collection of more comprehensive well information. ODNR can require supplemental permit application documentation such as seismic monitoring or seismic surveys, more geologic data, comprehensive well logs, a plan of action should seismicity occur, a step-rate test, falloff testing, a determination of the initial bottomhole pressure, and a series of operational controls: continuous pressure monitoring system, an automatic shut-off system, and an electronic data recording system for tracking fluids.

ODNR purchased nine portable seismic stations and has hired a PhD seismologist for the UIC Section to maintain and monitor the seismic network. ODNR is proactively approaching the issue of induced seismicity by conducting seismic monitoring at several new Class II injection well permit locations prior to commencement of injection operations and monitoring the seismicity for up to six months after initiation of injection operations. If no seismicity occurs, then these portable units will be moved to the next location.

Citations

ANSS: <http://quake.geo.berkeley.edu/cnss/>

Baranoski, M.T., 2002, in Structure Contour Map on the Precambrian Unconformity Surface in Ohio and Related Basement Features, Ohio Department of Natural Resources, Division of Geological Survey Map PG-23.

ODNR, 2004, Ohio Division of Geological Survey, Generalized column of bedrock units in Ohio: Ohio Department of Natural Resources, Division of Geological Survey, 1 p. http://www.dnr.state.oh.us/Portals/10/pdf/stratcol.pdf

ODNR, 2012, Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area: Ohio Department of Natural Resources, 24 p. plus figures. http://www.ohiodnr.com/home_page/NewsReleases/tabid/18276/EntryId/2711/Ohios-New-Rules-for-Brine-Disposal-Among-Nations-Toughest.aspx>.

Ohio Seismic Network: <http://www.ohiodnr.com/geosurvey/default/tabid/8144/Default.aspx>

Pennsylvania Geological Survey, 2005, Alexander, S. S., Cakir, R., Doden, A. G., Gold, D. P., and Root, S. I. (compilers), Basement depth and related geospatial database for Pennsylvania: Pennsylvania Geological Survey, 4th ser., Open-File General Geology Report 05-01.0, www.dcnr.state.pa.us/topogeo/openfile.

APPENDIX H: ASEISMIC EXAMPLES OF CLASS II DISPOSAL WELL ACTIVITY CAUSING LONG DISTANCE PRESSURE INFLUENCES

INTRODUCTION

Since pressure buildup is a key component to inducing seismicity, this appendix provides two examples of pressure buildup occurrences that impacted long distances. Neither example induced seismicity. The examples are included to illustrate abnormal cases of pressure buildup observed from two different Class II disposal well activities. The examples illustrate reservoir pressure distribution from disposal activities is site specific and dependent on geology and reservoir characteristics. The first example illustrates pressure movement through a linear trend and the second illustrates the cumulative pressure effect from multiple Class II wells completed in the same formation. These two examples also demonstrate the benefits of reservoir pressure measurements and the applicability and usefulness of pressure transient techniques.

The area of review determination for Class II disposal wells in the federal UIC regulations includes options for the calculation of the pressure buildup using radial flow equations or alternately using a fixed quarter mile radius from the disposal well without calculations (40 CFR §146.6). Reservoir quality or reservoir flow characteristics may extend pressure influence from the disposal activity beyond a ¼ mile radius from the well. If the reservoir pressure does not dissipate radially from the disposal well, use of the radial flow equations in the regulations may not be applicable for calculating the zone of endangering pressure influence. Reservoir pressure buildup is also additive, so offset wells completed in the same disposal zone may need to be considered. The Director can use discretionary authority to assess the area of review for special site specific circumstances.

EXAMPLE OF EXTENDED DIRECTIONAL PRESSURE TREND

BACKGROUND

Three inactive wells, two located approximately one mile from a Class II disposal well (5115’ and 6006’) and one just over ¼ mile (1584’) from the disposal well experienced an increase in surface pressure. These three wells were located in an east-northeast directional trend from the disposal well. The disposal well was the only well operating at a pressure exceeding the highest surface pressure measured at one of the inactive wells. The disposal well started injection approximately five months prior to discovering the increased pressure in the three abandoned wells. Other inactive wells located closer to the disposal well showed no pressure increase.

After identification of the potential well of concern, an interference testing procedure was designed to evaluate if the disposal well was hydraulically communicating with the inactive wells. The test was designed to establish repeatability of pressure responses if communication was present. The test also required monitoring fluid levels in additional wells, located outside the suspected directional trend, for possible pressure responses. A falloff test concluded the testing of the disposal well.

Interference Test Summary

As illustrated in Figure H-1, the interference test consisted of a background period, a one week stabilization period with the disposal well shut-in, one week with injection, and a one week falloff (shut in) period in the disposal well. During the injection period, the operator maintained as constant an injection rate as possible. No other active injection was present in the test area. During the background period, digital recording surface pressure gauges were installed on the disposal well and the three inactive wells experiencing surface pressures to monitor pressure responses during the test. The disposal well operator also installed an inline flow meter on the disposal well. In addition to surface pressure readings, fluid level measurements were collected at the other well locations.

Measured Offset Well Pressure Responses

As shown in Figures H-2 and H-3, the pressure response between the disposal well and three wells monitored with digital surface pressure gauges indicated direct communication. The repeatability of the pressure response was observed in all three wells. The lag time for the pressure response at each monitored well was much shorter than anticipated, and atypical of a radially homogeneous reservoir. The response times were not significantly different between the well located 1584’ from the disposal well and the two wells located 5115’ and 6006’ away. The magnitude of the pressure response varied, but a pressure response was still observed. The fluid levels monitored in other area wells plotted in Figure H-4 did not suggest any communication with the disposal well.

Analysis of Disposal Well Pressure Data

The disposal well pressure transient test data measurements, when reviewed and analyzed, indicated a strong linear flow signature. Pressure transient analysis provided an approach for identifying non-homogeneous, non-radial flow reservoir behavior at the disposal well. The elevated pressures from the disposal well exceeded the ¼ mile area of review allowed for Class II underground injection control permits. The reservoir's linear flow behavior could not be explained based on a review of available geologic and reservoir information. The disposal well was shut in and later plugged and abandoned.

The disposal well pressure responses were plotted in a log-log plot format as a diagnostic tool for identifying the flow regime signature away from the well. The log-log plots of the disposal well pressure response during the stabilization and falloff periods suggested bilinear (¼ slope) and linear (½ slope) reservoir flow characteristics (See Figure H-5). A bilinear (¼ slope) trend was observed for the entire test period during the stabilization whereas the falloff test period exhibited bilinear flow (¼ slope) followed by a linear flow characteristic (½ slope).

A simulation using PanSystem® pressure transient software, with a single fracture model, estimated a very low reservoir permeability and an unrealistically long fracture half length, nearly a mile in length (See Figure H-6). This fracture half length suggested the well was in communication with a linear fault system.

Monitoring Well Interference Tests

The pressure interference response recorded at the three inactive wells with surface transducers was also analyzed. The measured pressure response at all three wells located 1584', 5115', and 6006' in an east-northeast trend line from the disposal well was an easily measureable level with minimal lag time after a rate change at the disposal well. The repeatability of the results gave confirmation of the communication with the disposal well. The pressure transient test analyses of the interference data were marginal. The interference pressure responses measured at the three wells all demonstrated behavior outside the range of the Exponential Integral (Ei) type curve typically used for radial flow analysis, but did highlight the non-homogeneous nature of the disposal formation.

During the disposal well falloff period, the associated early time pressure response on the log-log plot for the well located 1584' east-northeast of the disposal well (See Figure H-7) exhibited a more rapid response than the typical Ei type curve, suggesting a naturally fractured reservoir characteristic or indication of directional permeability. The middle portion of the test matched to the Ei type curve estimated an unrealistically high (21 darcies) reservoir permeability before deviating off the type curve.

During the disposal well injection period, the early time pressure response from the well located 5115' east-northeast displayed two different Ei type curve responses on the log-log plot (See Figure H-8). The Ei type curve results from the front part of the test also estimated an unrealistically high (141 darcies) reservoir permeability, but a much lower permeability (28 md) was estimated from the Ei type curve match of the latter portion of the test.

During the stabilization period, the pressure response for the well located 6006’ from the disposal well also illustrated atypical pressure responses on the log-log plot (See Figure H-9). No match was attempted of the scattered early data. A type curve match in the middle portion of the test resulted in a permeability estimate of 488 md. The late time pressure response deviated off the Ei type curve.

The repeatable pressure response in the three abandoned wells confirmed that a linear pathway from the disposal well was present. Pressure transient testing at the disposal well also confirmed the presence of a linear flow environment. The interference test analyses also demonstrated a non-homogeneous reservoir.

Example of Cumulative Pressure Effect from Multiple Class II Wells

This second example covers a facility with a long history of recorded bottomhole pressure with a substantial increase in static reservoir pressure with no corresponding increase in injection rate.

Background

Disposal well operations with bottomhole pressure monitoring began in 1981. Disposal volumes at the pressure monitored disposal well (monitored well) facility remained relatively constant until reservoir pressure began increasing substantially in 2006 (See Figure H-10). The disposal interval ranges from 15-50 feet in thickness with an average permeability of 70 md and 13% porosity. No cause for the approximately 500 psi pressure increase was identified within two miles of the facility.

Expanded Review Area

A pressure transient analytical analysis was conducted using the above reservoir parameters along with a 35 ft net thickness, 0.54 cp viscosity and an injection rate of 100 gpm (3430 bpd). A pressure increase of 31 psi was predicted 15 miles away after 10 years of injection. The review area around the monitored well was expanded to 15 miles in an attempt to identify potential sources for the 500 psi reservoir pressure increase. Fourteen Class II disposal wells were identified as likely injecting into the same formation within a 15 mile radius of the monitored well (See Figure H-11). Additional Class II disposal wells exist beyond the 15 mile radius, but were not included for this demonstration.

Effects of Offset Disposal Activity

Most of the offset disposal activity began in late 2005 (See Figure H-12). The monitored well is included in the cumulative well count on Figure H-12. One offset well has operated occasionally for an extended period of time, but the majority of the offset disposal activity is more recent. Figure H-10 illustrates the disposal volumes of the monitored well and cumulative disposal volumes from the other fourteen wells located within the 15 mi radius.

APPENDIX I: PARADOX VALLEY, COLORADO

The U.S. Bureau of Reclamation runs a deep, high pressure, Class V disposal well in Paradox Valley, Colorado. This operation is part of the Colorado River Basin Salinity Control Project to remove near surface brine and limit saline flow into the Dolores River. Disposal is into the Mississippian carbonate and the upper Precambrian granite, e.g., basement rock. Prior to completion of the well, a ten station seismic network was installed in the area. Upgrades are made to the seismic network and the coverage area has been enlarged as necessary.

Figure I-1 contains two figures, the top shows the number and magnitude of events related to the distance from the disposal well. The lower figure adds the injection rate. Only one earthquake was recorded prior to injection starting in 1991. Numerous earthquakes followed the start-up of disposal operations, injection and stimulation tests (Phase I injection). Project reports highlight the apparent correlation between close earthquakes (near-well at $\leq$ 4 km from the injector) and initial tests. Relatively continuous injection (Phase II injection) did not begin until July 1996. A NW earthquake cluster (between 6 and eight km of the injector), accompanied this activity in addition to the near-well cluster. In response to a third Northern cluster of earthquakes (<13 km) developing along with near-well magnitude 3.5 and 4.3 events, the injection rate was reduced in 2000, (Phase III injection) including a biannual 20-day shutdown. This method was initially effective in reducing the earthquake frequency and magnitude.

In January 2002, (Phase IV injection) the injectate mix changed from 70% brine and 30% fresh Dolores River water to 100% brine. Figure I-1 shows a 3 to 3.5M earthquake occurring in the second distance cluster at about this time, followed by a greater than 3.5M nearby event around the end of 2003. Figure I-2 illustrates the injection rates with surface and bottomhole pressures, top, middle, and lower plots respectively. The lower plot shows an immediate increase in downhole pressure followed the conversion to all brine. The 3.5M higher magnitude event coincides with earlier 3.5M events when downhole pressure exceeded an apparent downhole pressure threshold. In 2004 a SE cluster of earthquakes (see Figure I-3) started, which increased in frequency in 2010.

More than 5,800 earthquake events have occurred since initial injection activities began in the area. There is minimal geosciences information along the northern edge of the valley. The Precambrian basement has not yet been modeled. The Precambrian earthquakes in the center of the valley are not well located. Currently a search for a second disposal well location is underway, (Block, et al, 2012).

Citations for Paradox Valley (Class V) Disposal Well

Ake, J. et al., 2002, What's shaking in bedrock? Paradox Valley deep-well injection program: Outcrop, v. 51, no. 4.

Ake, J. et al., 2005, Deep-injection and closely monitored induced seismicity at Paradox Valley, Colorado: Bulletin Seismological Society, v. 95, no. 2, p. 664-683.

Block, L., 2011, Paradox Valley deep disposal well and induced seismicity, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas, Bureau of Reclamation, US Department of the Interior.

Block, L., and Wood, C., 2010, 2010 annual report Paradox Valley seismic network, Paradox Valley Project, US Department of the Interior, Bureau of Reclamation.

Block, L., W. Yeck, V. King, S. Derouin, and C. Wood, 2012, Review of Geologic Investigations and Injection Well Site Selection, Paradox Valley Unit, Colorado; Technical Memorandum No. 86-68330-2012-27, Bureau of Reclamation, Denver, Colorado, 62 p., http://www.coloradoriversalinity.org/docs/CRB_TM_final_reduced.pdf

Bundy, J., 2001, World's deepest Class V disposal well in its 15th year, *in* Proceedings of the 2001 Ground Water Protection Council Annual Forum, Reno, Nevada, p. 90-98.

Mahrer, K. et al., 2005, Injecting brine and inducing seismicity at the world's deepest injection well, Paradox Valley, Southwest Colorado: Developments in Water Science, v. 52, p. 361-375.

FIGURE I- 1: INJECTION-INDUCED SEISMICITY & INJECTION RATES

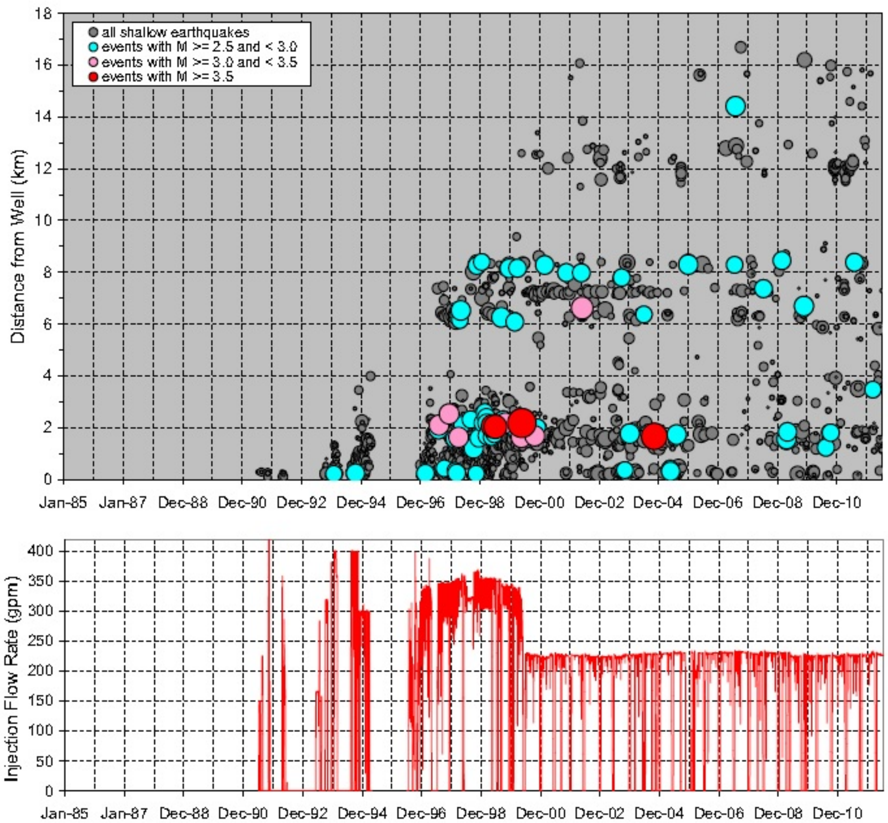


FIGURE I- 2: INJECTION RATE AND PRESSURES

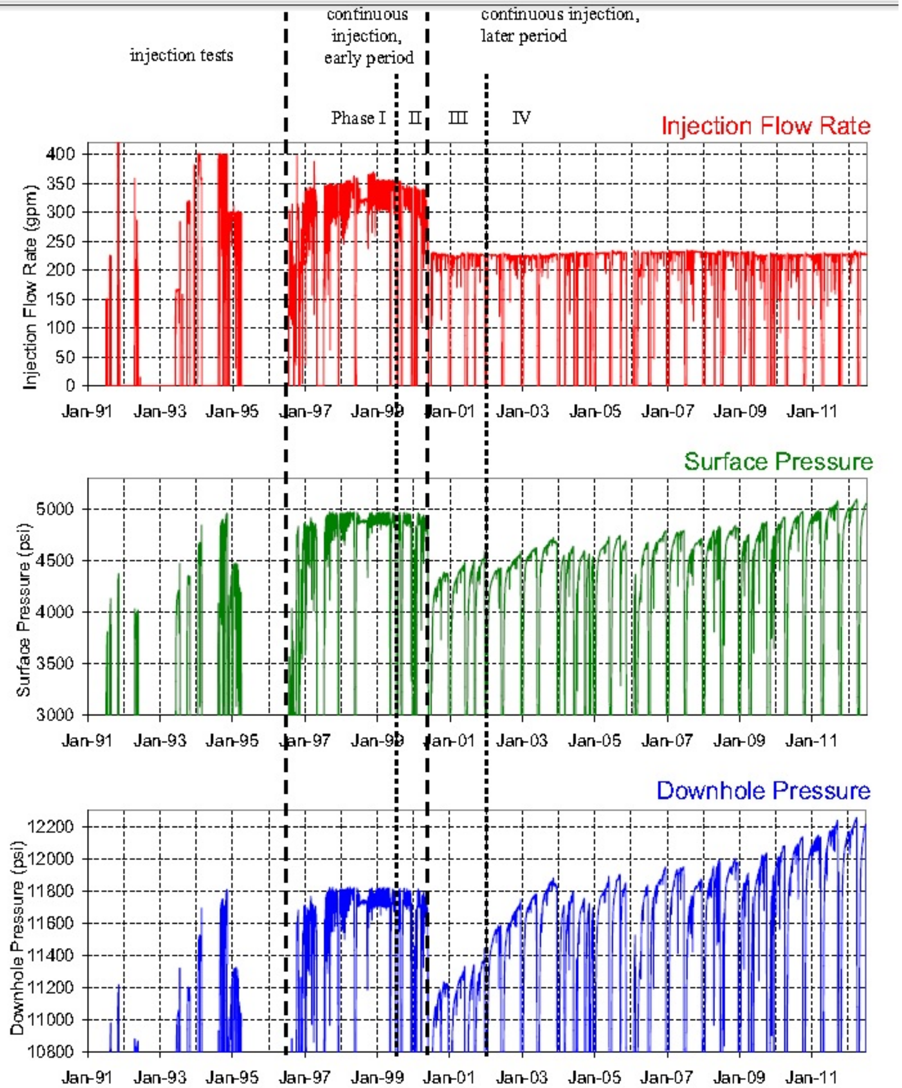


FIGURE I- 3: EARTHQUAKE CLUSTERS

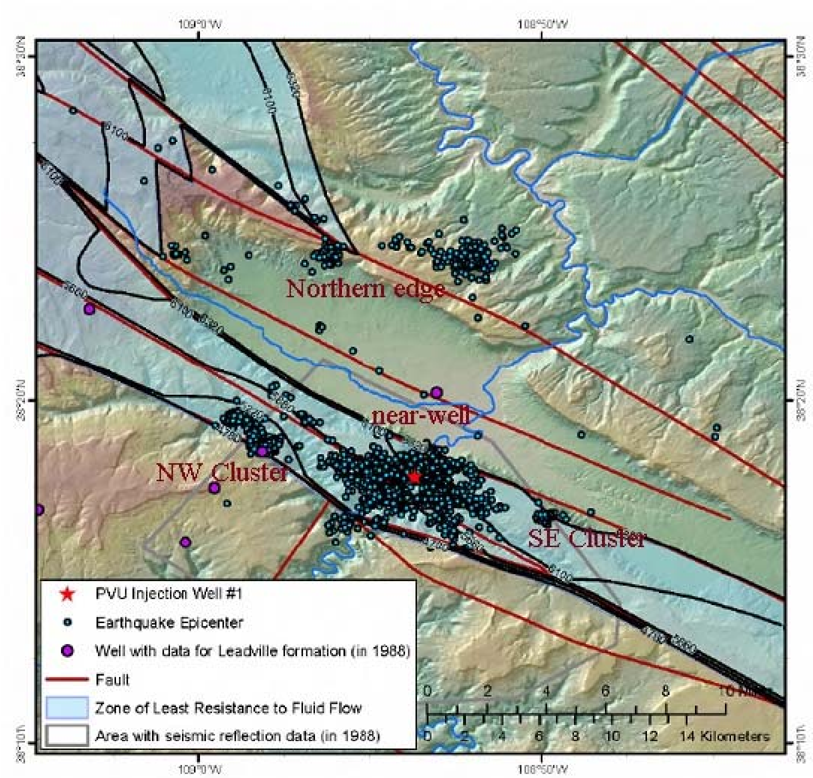


Figure 25: Contour map of hydrostatic pressure within the Leadville formation and predicted area of least resistance to fluid movement and pressure rise from injection into PVU Injection Well #1, from Bremkamp and Harr (1988) (drawing no. 2), and epicenters of shallow earthquakes interpreted to be induced by fluid injection into PVU Injection Well #1. (Fault traces were digitized from drawing no. 1, Bremkamp and Harr, 1988).

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APPENDIX J: GEOSCIENCE DISCUSSION & INTRODUCTION TO INDUCED SEISMICITY RISK

INTRODUCTION

A basic understanding of the earth science concepts and natural processes through geology; rock mechanics; and seismology, including the art and science of seismic interpretation is helpful in assessing the risks of inducing seismic events. A thorough discussion requires a working knowledge of both tectonic forces (physical stress and strain which change the shape of the earth's crust) and seismology—detailed topics outside the scope of this report. For any in-depth investigation (seismology, structural geology, reservoir characterization, etc.) consulting appropriate professionals is recommended, whether within your agency, a different agency (state or federal), professional society, academia or private industry. As geologic conditions can vary widely, no simplified approach to understanding fault movement and seismicity fits everywhere.

Information in this appendix was taken from Stein and Wysession, 2003; and Richard Sibson, 1994; along with a number of the websites cited at the end of this appendix and under 'Educational Websites' in the Subject Bibliography included as Appendix K.

BASIC EARTH SCIENCE CONCEPTS

The major earth layers or units are the core (inner and outer), mantle (inner and outer), and crust (oceanic and continental plates). Each unit has distinctly different characteristics and strengths. The oceanic plates are extremely dense and thin compared to the massive continental plates.

Over geologic time, convection currents within the mantle create both complex movements beneath the earth's crust and hot spots associated with volcanic areas. The resulting forces cause sea floor spreading and plate collisions along crustal plate boundaries. It is these processes that result in stressed conditions for crustal rocks deep below the ground surface and form the basis for the conclusion that all faults are critically stressed.

Within the Earth's crust, three-dimensional reactions to stress occur across every scale, from macro (plates) to micro (individual grains or crystals), according to the elastic or brittle properties of the affected material. Examples of brittle deformation in rocks include joints, complex fracture systems (including those formed from faulting or ductile folding) and faults, which are fractures along which there is significant movement. Faults in brittle formations are accompanied by fracture zones, which may extend some distance away from the fault. The frequency or density of fractures associated with a fault typically decreases with distance away from the fault. The nature of faulting and associated fracture zones is an important consideration with respect to induced seismicity since these fracture zones can serve as avenues of communication for pore pressure buildup to the fault. Although stress histories can be inferred in some cases by analysis of fracture patterns (e.g., analysis of joint patterns), areas that have been subjected to multiple tectonic events may have extremely complex and extensive fracture systems.

Basic Geologic Environment

A particular geographic area can be described in terms of three major geologic disciplines: stratigraphy (formation, sequence, and correlation of layered rock), petrology (rock origin to current condition), and structure (structural features and their causes). Petrology and stratigraphy use three main rock classifications (igneous, metamorphic and sedimentary) defined by rock origin, composition, and physical characteristics, among other details.

Stratigraphy primarily relates to geologic depositional processes and their order in time (law of superposition and identification of missing, repeated or overturned strata/sections). In the continental crust, the oldest (typically deepest) rock is called basement or crystalline basement and is formed through igneous or metamorphic processes. Sedimentary rocks (carbonates, evaporites and clastics) possibly with igneous intrusions (plutonic and volcanic) typically overlay the basement rocks. The contact between basement rocks and overlying younger strata is almost always an erosional surface (Narr et.al, 2006). Basement rocks usually have no effective primary permeability (connectivity of pore space) or porosity (void space), but later weathering or movement can result in fractures or erosional features creating significant secondary porosity. Faulting of basement rocks can result in fracture porosity and permeability along the fault zone. Basement faults that are active after deposition of overlying material can extend upward into overlying rock. Younger faults may also be present only in overlying sedimentary rocks.

Stratigraphic formations used as disposal zones can have a complex range of porosity types and permeability values. Sedimentary processes include precipitation (chemical and biological) and deposition of the rock particles eroded in-place or transported by water or air and later compacted into rock. The nature of fracture and matrix (bulk rock) porosities and permeabilities within the disposal zone is a critical aspect of pressure buildup from injection. Natural fractures can provide a permeable avenue for fluid flow while the matrix, generally being less permeable, offers more pore space potentially limiting pressure dissipation.

Petrology relates to the physical and chemical makeup of the rock, including how it is arranged (size and shape of pieces; void/pore space, cement overgrowths, dissolution, natural fractures, in-fill, etc.). In simplest terms, porosity is the primary storage capacity of the reservoir, and permeability determines how effectively fluids and pressure are transmitted within the reservoir. Generally, deeper rocks have less permeability and porosity than shallower rocks. Deep basement rocks (Precambrian) used for injection are usually either weathered (decomposed or altered), or the parent crystalline rock is fractured and faulted from tectonic forces. Wells injecting into intervals in proximity to or connected with fractured basement rock are more likely to induce seismicity.

The distribution and quality of porosity (both primary and secondary) and permeability within the disposal zone are critical for understanding how efficiently the formation will accept additional fluid. The area of increased pore pressure will be smaller in permeable and porous formations that allow fluids to move through the rock easily and quickly dissipate pore pressure, versus formations with restricted fluid movement and low porosity. Vertical and lateral variations in permeability and porosity are common in sedimentary rocks as are lateral variations in thickness of porous injection zones.

Geologic structure relates to the major physical changes in rock formations caused by three dimensional stresses. For example, earth stresses create fault and fracture zones; igneous intrusions; fold and thrust belts; wrench zones and metamorphosed (changed by heat and pressure) rock.

Geologic Interpretation Tools

Subsurface information on geologic structure can be inferred from surface geology, seismic data and information obtained from artificial penetrations. Under the UIC program, developing sufficient geoscience site data is the responsibility of the permit applicant. However, Regulatory agency programs may elect to review publications, or consult with geoscience agencies (state geologic surveys, USGS) for additional regional geologic information to address the areas of concern. Useful publications may include publicly or commercially available reports containing geologic information (history, stratigraphy or structure) and rock characterization (flow characteristics, fracture networks and stress directions), and also well logs, core analysis, mine surveys, seismic surveys and geologic presentations (maps and cross-sections).

Geologic demonstrations are designed to characterize the nature and continuity of the formations of interest (regional extent, depositional basin, major structural forces, mineral deposits, reservoirs, etc.). For example, a geologic isopach map or cross-section may define the lateral continuity of a disposal zone. An analysis of seismic data may help identify any deep seated faults, and if present, the extent of the fault or associated fractures. Fault identification depends on the quality of available seismic data, though near-vertical strike-slip faults may be missed. Correlations of logs or review of cross-sections may indicate missing sections or potential faults. Information on the origin, throw, and vertical extent of the fault should be evaluated for any potential impact on the disposal project.

Rock Mechanics

Earth scientists and engineers have developed various theories to explain observed fault motion/rock failure, with accompanying seismicity.

- The Mohr-Coulomb failure criterion is a fundamental rock mechanics model used to describe fracturing or faulting. The Mohr-Coulomb criterion uses the tectonic stresses on a fault, the frictional resistance of the fault materials, and the fluid pressure within the fault to determine whether or not movement will occur.
    - Motion occurs when shear stress along the fault matches or exceeds the frictional stress. (Sibson, 1994).
    - The Mohr-Coulomb criterion is generally applicable to the first few kilometers of the crust.
- Research is ongoing in a number of areas to define criteria not covered by Mohr-Coulomb. Examples of a few of these areas include time-dependence, localization, material heterogeneity and fracture propagation (Griffith Criteria), (Sibson, 1994; Beeler, et al, 2000; Pollard and Fletcher, 2005; Montési and Zuber, 2002).
- More information on deep stress fields and induced earthquakes provided by USGS, is available in Appendix M, Task 2.

Fault Motion

When sufficient movement or deformation occurs in the subsurface, a brittle rock will break during the deformation process, creating fractures. In contrast, a ductile rock will deform. Among the various sedimentary rock types, dolomite/limestone is one of the most brittle and clay/shale is the most flexible/ductile. Brittle rock may be more susceptible to inducing seismicity in a disposal environment.

At the other end of the spectrum, unconsolidated sediments are also subject to faulting and overpressure. Areas with high sedimentation rates, such as the Gulf of Mexico, develop growth faults in response to active compaction and gravity load on unstable slopes. The movement on the growth fault is triggered by episodic periods of heavy sediment load. Conversely, decreased pressure through pumping out ground water could also cause slip along the fault. Both causes effectively remove water from the sediment layer and increasing compaction of sediments, and hence increase the density and weight of the material triggering slip along the fault. Growth faults are also examples of shallow faulting unrelated to basement rocks.

Earth stress reactions will be accompanied by a level of seismicity that can be recorded with sufficiently sensitive and well placed monitor devices. The USGS has compiled a map database of all faults in the U.S. believed to have caused earthquakes above magnitude 6 in the last 1.6 million years, (USGS, 2004). The seismology community is actively studying the earth's structure, timing, and motion in an effort to not only understand but to also predict earthquakes. To grasp the difficulty in estimating seismicity potential, it is important to understand the basic aspects of seismicity, and how events are measured and interpreted.

Basic Seismology

A seismic event occurs when release of energy causes particle to particle wave motion below the earth's surface. Resulting waves move away from the release point. The event can be from a source in, on, or above ground that creates a 'shock' wave in the earth. The movement of the energy wave is governed by laws of refraction and reflection. Seismic exploration companies create energy waves to study the subsurface by using these properties to identify structure, layering, and/or exploitable components such as hydrocarbons. An earthquake (movement within the earth along a fault) gives rise to four types of seismic waves radiating away from the movement source (focus). These can be considered in two major wave categories, body waves and surface waves. Body waves travel through the Earth, while surface waves travel along the surface of the Earth. Body waves are faster than surface waves and are thus the first seismic waves to arrive; however, surface waves cause the most damage. Waves continue to travel until the energy is dissipated. Each of the four specific wave types has a characteristic motion (compressive, shear, or elliptical), frequency (wavelength) and velocity, with a corresponding wave equation. Travel times range from 2 to 7 kilometers per second, such that for a specific location there can be three to four arrival times of different waves in quick succession.

A large seismic event may trigger smaller ones with smaller sets of energy waves. In physics, crossing wave forms create either constructive or destructive interference. An earthquake series is a set of events related in space and time with similar characteristic wave signatures. In a series of earthquakes the largest event is the main shock, with the rest classified based on whether they occur before (foreshock) or after (aftershock). Detailed analysis of an earthquake series, with sufficiently detailed readings, can be used to map the probable fault location. Observation suggests that aftershocks are triggered by the mainshock, around the periphery of the fault displacement, as stresses are shifted to new locations. The length of time involved with respect to foreshocks and aftershocks is not uniformly defined, but the number of aftershocks decreases significantly over time after the mainshock (Richardson, 2013).

The relative size of an earthquake event can be described with different magnitude scales: local or Richter (M_L), surface-wave (M_s), body-wave (M_b) or Moment magnitude (M_w). The first three ($M_{L,}$ $M_{s\ and}$ M_b) use formulas combining amplitude from the seismometer recording with a distance correction from the recording(s) to the epicenter. Additionally, M_s and M_b incorporate the seismic wave period (peak to peak). M_b also includes an adjustment for the focal depth, (Alden, Geology.about.com website). M_L, M_s and M_b will provide similar results, but none are applicable to very large earthquakes (M>5).

Moment magnitude (M_w or M) is proportional to the release of energy from large earthquakes (Seismic Moment, M_o). The M_o equation is complex (rock rigidity, area and amount of movement or slip), (Richardson, Earth 502 website). M_w is applicable to all sizes of earthquakes, giving similar results to either $M_{s\ or}$ M_b for smaller earthquakes. There are multiple variations of the equation to convert M_o to M_w. In large earthquakes (M>5), the energy released is proportional to the amount of slip along the fault plane, (Wells and Coppersmith, 1994; Båth, 1966). In preparation of this report, EPA used magnitude values reported in earthquake catalogs (see Appendix M), for the case study evaluations.

The Modified Mercalli Intensity scale is discussed under the Seismic Risk section since it relates to damage resulting from an earthquake event.

Science and Art in Interpretation

Technology used for recording seismic waves has progressed from the original weighted spring or oscillating pendulum seismometers to complex electronic recorders that track motion in all directions. In addition to geologic events, seismometers also record ground motions caused by a wide variety of natural and man-made sources, such as cars and trucks on the highway, building demolition, and ocean waves crashing on the beach. Instrumentation improvements have provided enhanced recording sensitivity. The difference in quality of earthquake data from today's seismometers to those from twenty or thirty years ago should be considered when viewing historic earthquake data. Knowing the sophistication of the seismometer used to acquire the data is beneficial, noting that some older seismometers are still in service. Appendix M discusses the various earthquake database locations in greater detail.

The recordings of seismic events must be analyzed to determine the origin (latitude, longitude and depth) of the movement. At least three separate locations of seismograph readings are needed to locate the surface position (epicenter) of the earthquake. A model, with the major velocity layers, is used to separate the signals received into the different waves to determine the depth at which the earthquake occurred (hypocenter). Velocity is a function of rock porosity, fluid saturation, compaction and overburden pressure; or in rock mechanics terms, the elastic modulus, permeability and density. For earthquake modeling, the whole earth (surface through mantle) is divided into large layers with similar velocities. For exploration seismic modeling, a much more refined velocity model is needed to focus on the target interval.

Seismometers in the permanent monitor grid in most of the Continental U.S. are spaced up to 300 km apart. With this spacing, the system is capable of picking up events down to 3 or 3.5 magnitudes. In tectonically active areas such as the continental western margin and New Madrid Seismic Zone the seismometer spacing is tighter, resulting in more accurate measurement of event locations.

Beginning in 2007, the IRIS EarthScope Transportable Array has travelled systematically across the continental U.S. This array includes seismometers spaced every 70 km, and is capable of picking up events down to around magnitude 1. Subsequent research reports have concluded that the added modern seismometer density provided significant additional information, including improved seismicity rates for hazard analysis, and identification of earthquake swarms and clusters (Lockridge, et al, 2012, Frohlich, 2012). Consequently, the number of recorded seismic events over time is partly a function of the seismometer array density and instrument sensitivity.

Focal depths of the earthquakes are related to both the seismometer grid density and the detail (quantity and accuracy) of the model used to calculate it. Hypocenter depths are commonly reported using a default value for the geographic area model. On initial event notifications, default depths will have similar depth uncertainties. For example, a depth of 5 km may have a vertical uncertainty between three and five km. Generally, accurate focal depths (within less than 1000 feet vertically) are available only through special investigations, where the information from the seismometers is individually analyzed instead of computer picked.

According to the 2012 USGS glossary, the best located event has an uncertainty at the hypocenter of 100 m horizontally and 300 meters vertically. This may apply in California, but in the well constrained New Madrid seismic zone, deShon (2013) noted, “Absolute earthquake location is a function of location algorithm, velocity model, event-station geometry and pick quality.” She (deShon, 2013) found hypocenter locations moved up to seven km in depth and three km geographically, by incorporating different phases in the model.

Natural resource exploration firms have used various seismic reflection techniques for years to better view the subsurface heterogeneity. The additional quality gained by increased recording density from a regional two-dimensional (2D) survey to a tightly spaced three or four-dimensional survey is a striking improvement. Passive seismic recordings are now in use either in active seismic areas or producing fields with microseismicity, (Shemeta, et al, 2012; Verdon, et al, 2010; Martakis, et al, 2011).

To fit different needs, there are a series of different seismic event reports available from the USGS Earthquake website. Initial seismic event reports, generated within hours of the event, are designed to help with emergency response, and are very preliminary—with a wide range of location uncertainty. Later reports generally have increased accuracy (magnitude and location), as more information has been incorporated and the standard event modeling has been applied.

Seismic Risk

Seismic hazard represents the potential for serious seismic events, while risk is the potential damage to people and facilities. Induced seismicity risk evaluates the potential for triggering an earthquake sooner, by altering conditions and initiating movement along a preexisting, favorably oriented fault.

In 1977, Congress passed legislation to reduce the risks of life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program primarily designed to promote safe surface designs. As a result, USGS provides hazard maps used in risk assessments (Appendix M). Hazard typically relates back to magnitude while risk is associated with intensity. The intensity scale describes how strongly the earthquake was either felt or the degree of damage it caused at a specific location. A strong earthquake yields several different levels of intensity bands based on distance from event and corresponding surface geology. USGS has instituted a ‘Have you felt it?’ campaign to increase the epicenter location accuracy and to better define the intensity.

Surface and near surface structural designs are developed by engineers (mining, petroleum, nuclear, civil, etc.) for projects ranging from water reservoirs, deep tunnel construction, or horizontal well drilling. These designs incorporate detailed rock mechanics to withstand existing and potential stress, including seismically created stress (Pratt et all, 1978; Roberts, 1953; Schmitt, et al, 2012; Coppersmith, et al, 2012).

To understand how risk varies for surface versus subsurface structures, consider first the intensity difference. Seismic surface waves are the most likely to be felt, having the greatest amplitude and a motion similar to ocean waves. For the most damaging earthquakes, the earth moves very similar to the surface of the ocean in a storm. Consider the difference in motion on a ship at the top of the mast, main deck, and sea anchor. In simplistic terms, this would correspond to the top of a high-rise building, ground level structures, and deep structures such as a wellbore. Accordingly, a wellbore cemented through various layers of rock has a much lower motion potential at depth.

Most serious damage from a large earthquake results from effects of the earth surface movements on land such as collapsed infrastructure (buildings and dams leading to burial, flooding, fire and contamination), landslides (burial), and liquefaction (sinking). High seismicity risk is also present along coastlines from earthquake activity in the ocean (Tsunami), or on large bodies of water (seiche), in the form of large waves or erratic waves crashing on shorelines.

Most reports cover damage at or above surface ground level. The USGS compiled a summary of earthquakes, over 4.5 magnitude, in the United States between 1568 and 1989 (Stover and Coffman, 1527), describing in detail any damage that was observed inclusive of shallow and deep wells. The report covered tens of thousands of earthquakes. Forty three wells were mentioned predominantly in connection with temporary turbidity or fluid level changes with fewer than ten damage reports. Most of these wells were shallow water wells. Damage was frequently minor, from a tile falling off to a crack in the surface casing. The most applicable report was for the May 2, 1983, earthquake in Fresno County, California: "In the oil fields near Coalinga, surface facilities such as pumping units, storage tanks, pipelines, and support buildings were all damaged to some degree. … Subsurface damage, including collapsed or parted well casing, was observed only on 14 of 1,725 active wells."

UIC programs require that operators run a mechanical integrity test after an injection well workover (repair casing or replace tubing). The workover report typically lists the problem repaired, but does not identify the cause of the problem. UIC program directors also have discretionary authority, in cases of seismic events, to require additional measures such as mechanical integrity testing, as necessary to protect USDWs.

Seismology and Rock Mechanics Glossary

Earthquake is a series of vibrations induced in the earth's crust by the abrupt rupture and rebound of rocks in which elastic strain has been slowly accumulating. (dictionary.com) It is also the term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth. (USGS)

Earthquake hazard is anything associated with an earthquake that may affect the normal activities of people. This includes surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, tsunamis, and seiches. (http://earthquake.usgs.gov/-learn/glossary/?termID=64, downloaded 5/22/13)

Earthquake intensity is a number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Several scales exist, but the ones most commonly used in the United States are the Modified Mercalli scale and the Rossi-Forel scale. There are many intensities for an earthquake, depending on where you are, unlike the magnitude, which is one number for each earthquake. (USGS)

Earthquake magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used are (1) local magnitude (ML), commonly referred to as "Richter magnitude," (2) surface-wave magnitude (Ms), (3) body-wave magnitude (Mb), and (4) moment magnitude (Mw). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (Mw) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. All magnitude scales should yield approximately the same value for any given earthquake.

Earthquake risk is the probable building damage, and number of people that are expected to be hurt or killed if a likely earthquake on a particular fault occurs. Earthquake risk and earthquake hazard are occasionally incorrectly used interchangeably. (http://earth-quake.usgs.gov/learn/glossary/?term=earthquake risk, downloaded 5/22/13)

Epicenter is the 2D location of the earthquake source on the earth's surface, directly above the source, i.e. latitude, longitude.

Hypocenter aka focus is the 3D location of the earthquake source, i.e. latitude, longitude, focal depth below ground.

Radius of the earth is roughly 6,371 km (polar 6356.8 km and equatorial 6,378 km) (http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html, downloaded 5/22/13), with the core 3,485 km.

Period is the inverse of frequency, or one cycle of the wave shown in time units, versus wavelength in distance. It is equivalent to the wavelength divided by speed. This is the measure of time at the seismometer, peak to peak.

Rock mechanics is the study of the mechanical behavior of rocks, esp their strength, elasticity, permeability, porosity, density, and reaction to stress (dictionary.com)

Seiche is the sloshing of a closed body of water from earthquake shaking. Swimming pools often have seiches during earthquakes.

Shear in Mechanics or Geology is to become fractured along a plane as a result of forces acting parallel to the plane. (dictionary.com)

Shear Stress is the stress component acting tangentially to a plane, (Webster, 1995).

Shear Zone is a portion of rock mass traversed by closely spaced surfaces along which shearing has occurred; rock that may be crushed and brecciated, (Webster, 1995).

Stress is the physical pressure, pull, or other force exerted on one thing by another (dictionary.com), or the force of resistance within a solid body against alteration of form, (Webster, 1995).

a. the action on a body of any system of balanced forces whereby strain or deformation results.

b. the amount of stress, usually measured in pounds per square inch or in pascals.

c. a load, force, or system of forces producing a strain.

d. the internal resistance or reaction of an elastic body to the external forces applied to it.

e. the ratio of force to area.

Strain is deformation of a body or structure as a result of an applied force, or alternatively any force or pressure tending to alter shape, cause a fracture, etc. (dictionary.com)

Torsion in Mechanics (dictionary.com) is

a. the twisting of a body by two equal and opposite torques.

b. the internal torque so produced.

Torsional Stress is a shear stress on a transverse (direction at right angles to each other) cross-section resulting from a twisting action, (Webster, 1995)

Wavelength is one cycle of the wave shown in distance units. It is equivalent to speed times period, or speed divided by frequency. This is measured peak to peak at a single time.

CITATIONS

Alden, A., Earthquake Magnitudes: measuring the Big One, http://geology.about.com/cs/quakemags/a/aa060798.htm.

Båth, M., 1966, Earthquake energy and magnitude, m Physics and Chemistry of the Earth, vol 7, L H. Ahrens, F Press, S. K Runcorn, and H C. Urey, Editors, Pergamon Press, New York, 117-165.

Beeler, N. M., R. W. Simpson, S. H. Hickman and D.A. Lockner, 2000, Pore Fluid Pressure, Apparent Friction, and Coulomb Failure: Journal of Geophysical Research, v. 105, B11, p. 25,533-25,542.

deShon, H., 2013, Integrating USArray and Cooperative New Madrid Seismic Network Data to Establish Central US Catalog Location and Magnitude Sensitivities, USGS Award Number: G12AP20136, 18 p.

Frohlich, C., 2012, Induced or Triggered Earthquakes in Texas: Assessment of Current Knowledge and Suggestions for Future Research, USGS External Research Support, G12AP20001.

Frohlich, C., 2012, Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas: Proc. Nat. Acad. Sci., 109, 13934-13938.

Incorporated Research Institutions for Seismology (IRIS), Education and Public Outreach, http://www.iris.edu/hq/programs/education_and_outreach

Lockridge, J. S., M. J. Fouch, and J. R. Arrowsmith, 2012, Seismicity within Arizona during the Deployment of the EarthScope USArray Transportable Array: Bulletin of the Seismological Society of America, v. 102, n. 4, p. 1850–1863.

Martakis, N., A. Tselentis and P. Paraskevopoulos, 2011, High resolution passive seismic tomography -- a NEW exploration tool for hydrocarbon investigation, recent results from a successful case history in Albania, Article #40729, Search and Discovery, AAPG/Datapages, Inc.

Montési, L. G. and M. T. Zuber, 2002, A Unified Description of Localization for Application To Large-Scale Tectonics, Journal of Geophysical Research, v. 107, B3.

Narr, W., D. Schechter and L. Thompson, 2006, Naturally Fractured Reservoir Characterization, An Interdisciplinary Approach to Topics in Petroleum Engineering and Geosciences, Society of Petroleum Engineers, 112 p.

Richardson, E., 2011, Earth 520, Penn State, College of Earth and Mineral Sciences, https://www.e-education.psu.edu/earth520.

Pollard, D. D. and R. C. Fletcher, Fundamentals of Structural Geology, Cambridge University Press, 2005.

Pratt, H.R., W.A. Hustrulid, and D.E. Stephenson, 1978, Earthquake Damage to Underground Facilities: (http://www.osti.gov/bridge/servlets/purl/6441638-rVla3Q/6441638.pdf), p. 36-41.

Quest, Exploring the Science of Sustainability, http://science.kqed.org/quest/video/induced-seismicity-man-made-earthquakes/

Roberts, D. L., E. B. Hall and Co., 1953, Shear Prevention in the Wilmington Field, Drilling and Production Practice: American Petroleum Institute.

Schmitt, D. R., C. A. Currie, and L. Zhang, 2012, Crustal stress determination from boreholes and rock cores: Fundamental principles; Tectonophysics, v. 580, 10 December 2012, p. 1-26.

Shemeta, J., B. Goodway, M. Wiilis and W. Heigl, 2012, An introduction to this special section: Passive seismic and microseismic—Part 2, The Leading Edge December 2012, p. 1428-1435.

Sibson, R. H., 1994, Crustal Stress, Faulting and Fluid Flow: Geological Society Special Publication, v. 78, 1, p. 69-84.

St. Louis University, Ammon, C.A., An Introduction to Earthquakes & Earthquake Hazards, SLU EAS-A193, Class Notes, http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/notes_framed.html, last update 11/8/2010.

Stein, S., and M. Wysession, 2003, Introduction to Seismology, Earthquakes, and Earth Structure: Malden, Massachusetts, Blackwell Publishing, 498 p.

Stover, C.W. and J.L. Coffman, 1993, Seismicity of the United States, 1568-1989 (revised): USGS Professional Paper 1527, (http://pubs.usgs.gov/pp/1527/report.pdf).

United States Geologic Survey, Learn Earthquake Hazards Program, http://earthquake.usgs.gov/learn/

UP Seis an educational site for budding seismologists, Michigan Tech Geological and Mining Engineering and Sciences, http://www.geo.mtu.edu/UPSeis, last updated 4/16/2007.

USGS, 2004, Quaternary Fault and Fold Database of the United States, Fact Sheet 2004-3033, March 2004. For updated faults see 'Quaternary Faults' on http://earthquake.usgs.gov/hazards/?source=sitenav

USGS, Real-time & Historical Earthquake Information, http://earthquake.usgs.gov/earthquakes/?source=sitenav,ast Modified: September 25, 2013.

Verdon, J. P., J-M. Kendall and S. C. Maxwell, 2010, Comparison of passive seismic monitoring of fracture stimulation from water and CO_2 injection: Geophysics, v. 75, p. MA1-MA7.

Wells, D. L., and K. J. Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

APPENDIX K: SUBJECT BIBLIOGRAPHY

Injection induced seismicity is a rapidly expanding area of research. This list is not intended to serve as a complete resource list. Additionally, websites frequently shift links so that some may become inactive.

DISCLAIMER

Inclusion of an article or website in this Appendix does not represent EPA's agreement with the conclusion of the article.

Helpful Links

Associations & Surveys: Professional Scientific and Engineering

American Association of Petroleum Geologists, http://www.aapg.org/

Canadian Association of Petroleum Producers, http://www.capp.ca/aboutUs/mediaCentre/NewsReleases/Pages/Seismicitynaturalgasproducerstakestepstoensurecontinuedsafehydraulicfracturingoperations.aspx

Canadian Society of Exploration Geophysicists: Microseismic User Group (MUG), http://cseg.ca/technical/category/mug/

Colorado Geological Survey: http://geosurvey.state.co.us/Pages/CGSHome.aspx

Kansas Geological Survey: http://www.kgs.ku.edu/

Ohio Seismic Network: http://www.ohiodnr.com/geosurvey/default/tabid/8144/Default.aspx

Oklahoma Geologic Survey, http://www.okgeosurvey1.gov/pages/research.php

Seismological Society of America, http://www.seismosoc.org/

Society of Petroleum Engineers, http://www.spe.org/index.php

West Virginia Geological and Economic Survey: http://www.wvgs.wvnet.edu/

Earthquake Catalogs (excluding state)

Advanced National Seismic System (ANSS): http://www.ncedc.org/anss/catalog-search.html

Contributing Networks: http://www.ncedc.org/acknowledge.html

CERI/New Madrid Catalog: http://www.ceri.memphis.edu/seismic/catalogs/cat_nm.html

IRIS EarthScope Data:

Events: http://www.iris.edu/data/event/, or http://www.iris.edu/SeismiQuery/sq-events.htm

Seismometer stations and arrays: http://www.iris.edu/earthscope/usarray/

IRIS: http://www.iris.edu/SeismiQuery/sq-events.htm & http://www.iris.edu/dms/wilber.htm

ISC: http://www.isc.ac.uk/iscbulletin/search/bulletin/interactive/

NCEER: http://www.ceri.memphis.edu/seismic/catalogs/cat_nceer.html

USGS / NEIC: http://earthquake.usgs.gov/earthquakes/search/

Contributing networks: http://earthquake.usgs.gov/earthquakes/map/doc_aboutdata.php

EDUCATIONAL WEBSITES ON SEISMICITY

Richardson, E., 2011, Earth 520, Penn State, College of Earth and Mineral Sciences, https://www.e-education.psu.edu/earth520.

Quest, Exploring the Science of Sustainability, http://science.kqed.org/quest/video/induced-seismicity-man-made-earthquakes/

United States Geologic Survey,

Learn Earthquake Hazards Program, http://earthquake.usgs.gov/learn/

U. S. Seismic Design Maps, http://earthquake.usgs.gov/hazards/designmaps/usdesign.php

New Mexico Bureau of Geology and Mineral Resources, Earthquake Education and Resources, http://tremor.nmt.edu/, last modified 1/3/2008.

Lawrence Berkley National Laboratory Earth Sciences Division, Induced Seismicity Primer, http://esd.lbl.gov/research/projects/induced_seismicity/primer.html#defined

Digital Library for Earth System Education (DLESE) Teaching Boxes, Living in Earthquake Country (6-12), http://www.teachingboxes.org/earthquakes/index.jsp

Tasa Clips Images for the geosciences, Animations, see various faulting, earthquake and seismic wave related clips, http://www.tasaclips.com/animations

UP Seis an educational site for budding seismologists, Michigan Tech Geological and Mining Engineering and Sciences, http://www.geo.mtu.edu/UPSeis, last updated 4/16/2007.

St. Louis University, Ammon, C.A., An Introduction to Earthquakes & Earthquake Hazards, SLU EAS-A193, Class Notes, http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/notes_framed.html, last update 11/8/2010.

Incorporated Research Institutions for Seismology (IRIS), Education and Public Outreach, http://www.iris.edu/hq/programs/education_and_outreach

& Purdue University Department of Earth & Atmospheric Science, Briale, L. W., Seismic Waves and the Slinky: A guide for Teachers, http://web.ics.purdue.edu/~braile/edumod/slinky/slinky.htm, last modified 2/24/2010.

Seismological Society of America, SSA< Publications, http://www.seismosoc.org/publications/

PBS LearningMedia, http://www.pbslearningmedia.org/search/?q=earthquakes, search on earthquakes.

Space Geology Laboratory, NASA Doddard Space Flight Center, Kuang, W., MoSST Core Dynamics Model, Research Project on Earth & Planetary Interiors,http://bowie.gsfc.nasa.gov/MoSST/index.html

California Geologic Survey, Natural Hazards Disclosure-Seismic Hazard Zones, State of California Department of Conservation, http://www.conservation.ca.gov/cgs/shzp/Pages/shmprealdis.aspx

NASA Earth Fact Sheet, http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html

Dictionary, http://www.dictionary.com,

Industry Websites on Casing damage

http://www.terralog.com/casing_damage_analysis.asp

World Stress Map Project : http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction_frame.html

Useful Publisher or Other Search Engines (abstracts usually free)

AAPG Datapages, (http://archives.datapages.com/data)

GeoScience World, (www.geoscienceworld.org/search)

One Petro, (http://onepetro.org)

Seismological Society of America, (SSA), also search through Geo Science World

Bulletin of the SSA, (http://www.bssaonline.org/search)

Seismological Research Letters, (http://www.seismosoc.org/publications/srl/web-index.php)

Science Direct, (http://www.sciencedirect.com/)

Wiley Online Library, (http://onlinelibrary.wiley.com)

General Information and Protocols

Båth, M., 1966, Earthquake energy and magnitude, Physics and Chemistry of the Earth, vol 7, L H. Ahrens, F Press, S. K Runcorn, and H C. Urey, Editors, Pergamon Press, New York, 117-165.

Coplin, L. S., and D. Galloway, 2007, Houston-Galveston, Texas Managing coastal subsidence: <http://pubs.usgs.gov/circ/circ1182/pdf/07Houston.pdf>.

Davis, S. D., and C. Frohlich, 1993, Did (or will) fluid injection cause earthquakes? Criteria for a rational assessment: Seismological Research Letters, v. 64, no. 3-4.

Deichmann, N., 2010, Injection-induced seismicity: Placing the problem in perspective, International Conference: Geothermal Energy and Carbon Dioxide Storage: Synergy or Competition?: Potsdam, Germany.

GWPC, 2013, A White Paper Summarizing a Special Session on Induced Seismicity: (http://www.gwpc.org/events/gwpc-proceedings/2013-uic-conference scroll down)

Majer, E., J. Nelson, A. Robertson-Tait, J. Savy, and I. Wong, 2011, Protocol for addressing induced seismicity associated with enhanced geothermal systems, Accessed November 22, 2011, <http://www1.eere.energy.gov/geothermal/pdfs/egs-is-protocol-final-draft-20110531.pdf>.

Majer, E. L., R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith and H. Asanuma, 2007, Induced seismicity associated with enhanced geothermal systems: Geothermics, v. 36, p. 185-222.

National Research Council, 2013, Induced Seismicity Potential in Energy Technologies, The National Academies Press, (http://www.nap.edu/catalog.php?record_id=13355).

Nygaard, K. J., J. Cardenas, P. P. Krishna, T. K. Ellison, and E. L. Templeton-Barrett, 2013, Technical Consideration Associated with Risk Management of Potential Induced Seismicity in Injection Operations, Sto. Congreso de Producci6n y Desarrollo de Reservas Rosario, Argentin, May 21 -24, 2013.

Pollard, D. D. and R. C. Fletcher, Fundamentals of Structural Geology, Cambridge University Press, 2005.

Stein, S., and M. Wysession, 2003, Introduction to Seismology, Earthquakes, and Earth Structure: Malden, Massachusetts, Blackwell Publishing, 498 p.

US Geological Survey, 1995, The October 17, 1989, Loma Prieta, California, Earthquake - Selected Photographs, US Geological Survey, Accessed December 15, 2011 (http://pubs.usgs.gov/dds/dds-29/), Last updated July 2, 2009.

Wells, D. L., and K. J. Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

Journal Editions Dedicated to Induced Seismicity

Journal of Seismology, 2012, v. 17: special issue Triggered and induced seismicity: probabilities and discrimination, p. 1-202.

The Leading Edge, 2012, v. 31, November, Special Section: Passive Seismic and Microseismic, Part 1, p. 1296-1354.

The Leading Edge, 2012, v. 31, December, Special Section: Passive Seismic and Microseismic, Part 2, p. 1428-1511.

Geothermal

Asanuma, H., Y. Mukuhira, H. Niitsuma, and M. Häring, 2010, Investigation of physics behind large magnitude microseismic events observed at Basel, Switzerland, Second European Geothermal Review -- Geothermal Energy for Power Production: Mainz, Germany.

Deichmann, N., and D. Giardini, 2009, Earthquakes induced by the stimulation of an enhanced geothermal system below Basel (Switzerland): Seismological Research Letters, v. 80, no. 5, p. 784-798.

Giardini, D., 2011, Induced seismicity in deep heat mining: Lessons from Switzerland and Europe, Presentation for National Academy of Science.

Häring M.O., U. Schanz, F. Ladner and B. Dyer, 2008, Characterization of the Basel 1 enhanced geothermal system, Geothermics, v. 37, p. 469-495.

Lagenbruch, C. and S. A. Shapiro, 2010, Decay rate of fluid-induced seismicity after termination of reservoir stimulations, v. 75, n. 6, p 53-62.

Majer, E., R. Baria and M. Stark, 2008, Protocol for induced seismicity associated with enhanced geothermal systems, Report produced in Task D Annex I: International Energy Agency - Geothermal Implementing Agreement (incorporating comments by Bromley, C., W. Cumming, A. Jelacic and L. Rybach).

Majer, E., Majer, E., R. Baria and A. Jelacic, 2006, Cooperation to address induced seismicity in enhanced geothermal systems, Presentation at Geothermal Resources Council Annual Meeting Sept. 10-13 San Diego, California.

Nathwani, J., 2011, DOE Geothermal Technologies Program and induced seismicity: Presentation for National Academy of Science.

Nummedal, D., G. Isaksen and P. Malin, 2013, 2011 Napa Hedberg Research Conference report on enhanced geothermal systems, AAPG Bulletin, v. 97, no. 3, p. 413–420.

Shalev, E. and V. Lyakhovsky, 2013, Modeling Reservoir Simulation Induced by Wellbore Fluid injection: PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198.

Tenthoreya, E., S. Vidal-Gilbert, G. Backé, R. Puspitasaric, Z. J. Pallikathekathilc, B. Maneyd, and D. Dewhurst, 2013, Modelling the geomechanics of gas storage: A case study from the Iona gas field, Australia: International Journal of Greenhouse Gas Control v. 13, p. 138–148.

Induced Seismicity Report Four Case Studies

Arkansas Case Studies

2008, General rule G-43 Well Spacing Area, Faulkner County, Arkansas: Commission review of applicant's request: Order No. 63-2008-01: El Dorado, Arkansas Oil and Gas Commission, p. 3.

Ausbrooks, S.M. and Doerr, E., 2007, Enola Swarm Area-Faulkner County, Arkansas: GH-EQ-ENOLA-002, Arkansas Geological Survey, 1 sheet.

Ausbrooks, S. M., 2011, Exhibit 23: Geologic overview of north-central Arkansas and the Enola and Guy-Greenbrier earthquake swarm areas, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011, Exhibit 24: Overview of the E. W. Moore Estate No. 1 well (Deep Six SWD) and small aperture seismic array, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011, Exhibit 25: Clarita Operating, LLC, Wayne Edgmon SWD data, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011, Exhibit 30: Docket 063-2008-01, initial Deep Six permit hearing, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011, Guy Area 3D model final (hearing submission not presented), *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Ausbrooks, S. M., 2011, Recent NCAR earthquakes and comparison of the Enola and Guy earthquake swarms in north-central Arkansas, 2011, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Horton, S. P., 2011, Exhibit 22: Central Arkansas earthquake activity: Draft of testimony to Arkansas Oil and Gas Commission, *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

Horton, S. P., 2012 Disposal of Hydrofracking-waste fluid by injection into subsurface aquifers triggers earthquake swarm in Central Arkansas with potential for damaging earthquakes: Seismological Research Letters, v. 83, p. 250-260 also Ausbrooks and Horton, 2013: GWPC 2013 Proceedings, Day 2.

Horton, S., and S. M. Ausbrooks, 2011, Earthquakes in central Arkansas triggered by fluid injection at Class 2 UIC wells, National Academy of Science Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas.

McFarland, J. D., and S. M. Ausbrooks, 2010, The 2005 Arkansas New Madrid earthquakes: Arkansas Geological Survey.

Rabak, I., C. Langston, P. Bodin, S. Horton, M. Withers, and C. Powell, 2010, The Enola, Arkansas, Intraplate Swarm of 2001: Seismological Research Letters, v. 81, n. 3, p. 549-559.

USGS, 2011, New Madrid 1811-1812 earthquakes, US Geological Survey, Accessed November 22 <http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php>, Last updated May 24, 2011.

USGS, 2011, Poster of the 2010-2011 Arkansas Earthquake Swarm, US Geological Survey: <http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2011/20110228.php>.

Fort Worth Basin Case Studies and Geology

Bruner, K. R., and R. Smosna, 2011, A comparative study of the Mississippian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin: US Department of Energy, National Energy Technology Laboratory.

Eisner, L., 2011, Seismicity of DFW, Texas, *in* Presentation for Academy of Sciences of the Czech Republic.

Ewing, T. E., 2006, Mississippian Barnett Shale, Fort Worth Basin, northcentral Texas: Gas-shale play with multi-trillion cubic foot potential: Discussion: AAPG Bulletin, v. 90, no. 6, p. 963-966.

Ficker, E., 2012, Five Years of Deep Disposal into the Ellenburger of the Fort Worth Basin: Search and Discovery Article 80227, Posted June 11, 2012.

Frohlich, C., 2011, Induced Texas earthquakes: What could more research tell us?, *in* Presentation for National Academy of Science, University of Texas at Austin.

Frohlich, C., 2012, A survey of earthquakes and injection well locations in the Barnett Shale, Texas: The Leading Edge, December 2012, v. 31, p. 1446-1451.

Frohlich, C., 2012, Induced or Triggered Earthquakes in Texas: Assessment of Current Knowledge and Suggestions for Future Research, USGS External Research Support, G12AP20001.

Frohlich, C., 2012, Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas: Proc. Nat. Acad. Sci., 109, 13934-13938.

Frohlich, C., C. Hayward, B. Stump, and E. Potter, 2011, Dallas-Fort Worth earthquake sequence: October 2008 through May 2009: Bulletin of the Seismological Society of America, v. 101, p. 327-340.

Frohlich, C., E. Potter, C. Hayward, and B. Stump, 2010, Dallas-Fort Worth earthquakes coincident with activity associated with natural gas production: The Leading Edge, v. 29, no. 3, p. 270-275.

Howe, A., M. (2012). Analysis of Cleburne Earthquakes from June 2009 to June 2010, M.S. thesis, Southern Methodist University, 102 pp.

Howe---Justinic, A. M., B. S. Stump, C. Hayward, and C. Frohlich (2012, submitted). Analysis of the Cleburne earthquake sequence from June 2009 to June 2010: Bulletin of the Seismological Society of America.

Janská, E. and L. Eisner, 2012, Ongoing seismicity in the Dallas-Fort Worth area: The Leading Edge, v. 31, p. 1462-1468.

Loucks, R. G., and S. C. Ruppel, 2007, Mississippian Barnett Shale: Lithofacies and depositional setting of a deep-water shale-gas succession in the Fort Worth Basin, Texas: AAPG Bulletin, v. 91, no. 4, p. 399-403.

Martineau, D. F., 2007, History of the Newark East field and the Barnett Shale as a gas reservoir: AAPG Bulletin, v. 91, no. 4, p. 399-403.

McDonnell, A., R. G. Loucks, and T. Dooley, 2007, Quantifying the origin and geometry of circular sag structures in northern Forth Worth Basin, Texas: Paleocave collapse, pull-apart fault systems, or hydrothermal alteration?: AAPG Bulletin, v. 91, no. 9, p. 1295-1318.

Montgomery, S. L., D. M. Jarvie, K. A. Bowker, and R. M. Pollastro, 2006, Mississippian Barnett Shale, Fort Worth Basin, northcentral Texas: Gas-shale play with multi-trillion cubic foot potential: Reply: AAPG Bulletin, v. 90, no. 6, p. 967-969.

Montgomery, S. L., D. M. Jarvie, K. A. Bowker, and R. M. Pollastro, 2005, Mississippian Barnett Shale, Fort Worth Basin, northcentral Texas: Gas-shale play with multi-trillion cubic foot potential: AAPG Bulletin, v. 89, no. 2, p. 155-175.

Reiter, D., M. Leidig, S-H. Yoo and K. Mayeda, 2012, Source characteristics of seismicity associated with underground wastewater disposal: A case study from the 2008 Dallas-Fort Worth earthquake sequence: The Leading Edge, v. 31, 1454-1460.

Steward, D. B., 2011, The Barnett Shale oil model of North Texas, Article #110151, Search and Discovery, AAPG/Datapages, Inc., posted June 13, 2011.

OHIO

Ahmad, M. U., and J. A. Smith, 1988, Earthquakes, injection wells, and the Perry Nuclear Power Plant, Cleveland, Ohio: Geology, v. 16, no. 8, p. 739-742.

Alexander, S. S., R. Cakir, A. G. Doden, D. P. Gold and S. I. Root, (compilers), 2005, Basement depth and related geospatial database for Pennsylvania: Pennsylvania Geological Survey, 4th ser., Open-File General Geology Report 05-01.0, www.dcnr.state.pa.us/topogeo/openfile.

Baranoski, M.T., 2002, in Structure Contour Map on the Precambrian Unconformity Surface in Ohio and Related Basement Features, Ohio Department of Natural Resources, Division of Geological Survey Map PG-23.

Gerrish, H., and A. Nieto, 2003, Review of injection reservoir information in relation to earthquakes in Ashtabula, Ohio, 2nd International Symposium, Underground Injection Science and Technology: Symposium Abstracts: Berkeley, California, Lawrence Berkeley National Laboratory, p. 156.

S. Holtkamp, B. Currie, and M. R. Brudzinski, 2013, A More Complete Catalog of the 2011 Youngstown, Ohio Earthquake Sequence from Template Matching Reveals a Strong Correlation to Pumping at a Wastewater Injection Well, AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22.

Kim, W-Y, 2013, Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio, Journal of Geophysical Research: Solid Earth, v. 118, p. 3506-3518.

ODNR, 2004, Ohio Division of Geological Survey, Generalized column of bedrock units in Ohio: Ohio Department of Natural Resources, Division of Geological Survey, 1 p. <http://www.dnr.state.oh.us/Portals/10/pdf/stratcol.pdf>.

ODNR, 2012, Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area: Ohio Department of Natural Resources, 24 p. plus figures. http://www.ohiodnr.com/home_page/NewsReleases/tabid/18276/EntryId/2711/Ohios-New-Rules-for-Brine-Disposal-Among-Nations-Toughest.aspx>.

Ohio Seismic Network: <http://www.ohiodnr.com/geosurvey/default/tabid/8144/Default.aspx>

Seeber, L., and J. Armbruster, 1993, Natural and induced seismicity in the Lake Erie-Lake Ontario region: reactivation of ancient faults with little neotectonic displacement: Géographie physique et Quaternaire, v. 47, n. 3, p. 363-378.

Seeber, L., and J. Armbruster, 2004, A fluid-injection-triggered earthquake sequence in Ashtabula, Ohio: Implications for seismogenesis in stable continental regions: Bulletin of the Seismological Society of America, v. 94 n. 1, p. 76-87.

Tomastik, T., 2013, Preliminary Report on the Northstar #1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area: GWPC 2013 Proceedings, Day 2.

Wesson, R. L., and C. Nicholson, 1986, Studies of the January 31, 1986, northeastern Ohio earthquake, US Geological Survey, Open-File Report 86-331.

West Virginia

Avary, K. L., 2011, Overview of gas and oil resources in West Virginia, West Virginia Geological & Economic Survey.

Bass, T., 2013, West Virginia DEP, Office of Oil & Gas: GWPC 2013 Proceedings, Day 2.

Boyce, M. L., and T. R. Carr, 2009, Lithostratigraphy and petrophysics of the Devonian Marcellus interval in West Virginia and southwestern Pennsylvania: Morgantown, West Virginia University, p. 25.

Bruner, K. R., and R. Smosna, 2011, A comparative study of the Mississippian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin: US Department of Energy, National Energy Technology Laboratory.

Other Induced Seismicity Studies

Cox, R.T., 1991, Possible triggering of earthquakes by underground waste disposal in the El Dorado, Arkansas area: Seismological Research Letters, v. 62, p. 113-122.

de Pater, C. J., and S. Baisch, 2011, Geomechanical study of Bowland Shale seismicity synthesis report: Cuadrilla Resources.

Eager, K. C., G. L. Pavlis and M. W. Hamburger, 2006, Evidence of possible induced seismicity in the Wabash Valley Seismic Zone from improved microearthquake locations: Bulletin of the Seismological Society of America, v. 96, no. 5, p. 1718-1728.

El Hariri, M., R. E. Abercrombie, C. A. Rowe and A. F. do Nascimento, 2010, Role of fluids in triggering earthquakes: Observations from reservoir induced seismicity in Brazil: Geophysical Journal International, v. 81, no. 3, p. 1566-1574.

Frohlich, C. and M. Brunt, 2013, Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the Mw 4.8 20 October 2011 earthquake, Earth and Planetary Science Letters, v. 379, p. 56-63.

Kanamori, H. and E. Hauksson, 1992, A slow earthquake in the Santa Maria Basin, California: Bulletin of the Seismological Society of America, v. 82, p. 2087-2096.

McGarr, A., D. Simpson, and L. Seeber, 2002, Case Histories of Induced and Triggered Seismicity: in Lee WHK, Kanamori H, Jennings PC, Kisslinger C (eds) *International Handbook of Earthquake and Engineering Seismology*, v. 81A, Academic Press, Amsterdam, p. 647-661.

Nicholson, C., and R. L. Wesson, 1990, Earthquake hazard associated with deep well injection, *in* Bulletin, U. G. S., ed.

Nicholson, C., and R. L. Wesson, 1992, Triggered earthquakes and deep well activities: Pure and Applied Geophysics, v. 139, no. 3-4, p. 561-568.

Porsani, J. L., E. R. Almeida, C. A. Bortolozo. And F. A. Monteiro dos Santos, 2012, TDEM survey in an area of seismicity induced by water wells in Paraná sedimentary basin, Northern São Paulo State, Brazil: Journal of Applied Geophysics v. 82, p. 75–83.

Stevenson, D. A., and J. D. Agnew, 1983, Lake Charles, Louisiana, Earthquake OF 16 October 1983: Bulletin of the Seismological Society of America, v. 78, no. 4, p. 1463-1474.

Suckale, J., 2009, Induced seismicity in hydrocarbon fields: Advances in Geophysics, Academic Press, p. 55-106.

Suckale, J., 2010, Moderate-to-large seismicity induced by hydrocarbon production: The Leading Edge, v. 29, no. 3, p. 310-319.

COLORADO

2002, We don't have earthquakes in Colorado do we?: Rock Talk, Colorado Geological Survey.

1988, Army Corps of Engineers, Final Report on Drilling of Pressure Injection Disposal Well Rocky Mountain Arsenal Denver, Colorado, AD667358.

Ake, J., L. Block, D. O'Connell, 2002, What's shaking in bedrock? Paradox Valley deep-well injection program: Outcrop, v. 51, no. 4.

Ake, J., K. Mahrer, D. O'Connell and L. Block, 2005, Deep-injection and closely monitored induced seismicity at Paradox Valley, Colorado: Bulletin Seismological Society, v. 95, no. 2, p. 664-683.

Block, L., 2011, Paradox Valley deep disposal well and induced seismicity, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas, Bureau of Reclamation, US Department of the Interior.

Block, L., and C. Wood, 2010, 2010 annual report Paradox Valley seismic network, Paradox Valley Project, US Department of the Interior, Bureau of Reclamation.

Block,L., C. Wood, W. Yeck, King, V., (pending submission), The January 24, 2013 ML 4.4 earthquake near Paradox, Colorado and its relation to deep well injection, Seismological Research Letters.

Block, L., W. Yeck, V. King, S. Derouin, and C. Wood, 2012, Review of Geologic Investigations and Injection Well Site Selection, Paradox Valley Unit, Colorado; Technical Memorandum No. 86-68330-2012-27, Bureau of Reclamation, Denver, Colorado, 62 p., http://www.coloradoriversalinity.org/docs/CRB_TM_final_reduced.pdf

Bundy, J., 2001, World's deepest Class V disposal well in its 15th year, *in* Proceedings of the 2001 Ground Water Protection Council Annual Forum, Reno, Nevada, p. 90-98.

Ellsworth, S., 2013, Colorado Oil and Gas Conservation Commission Underground Injection Control (UIC) Seismicity: GWPC 2013 Proceedings, Day 2.

Flak, L. H. and J. J. Brown, 1990, Case History of an Ultradeep Disposal Well in Western Colorado, SPE Drilling Engineering, v. 5, no. 1, p. 39-44.

Gibbs, J.F., J.H. Healy, C.B. Raleigh, and J. Coakley, 1972, Earthquakes in the oil field at Rangely, Colorado: U.S. Geological Survey Open File Report 72–130, 48 p.

Healey, J. H., W.W. Rubey, D.T. Griggs and C.B. Raleigh, 1968, Denver earthquakes: Science, v. 161, no. 3848, p. 1301-1310.

Hsieh, P. A., and J. D. Bredehoeft, 1981, Reservoir Analysis of the Denver earthquakes: A case of induced seismicity: Journal of Geophysical Research, v. 86, no. B2, p. 903-920.

King, V., L. Block, W. Yeck, C. Wood, and S. Derouin, (submitted 2013), Geological Structure of the Paradox Valley Region, Colorado, and Relationship to Seismicity Induced by Deep Well Injection, Journal of Geophysical Research: Solid Earth.

Mahrer, K., J. Ake, L. Block, D. O'Connell and J. Bundy, 2005, Injecting brine and inducing seismicity at the world's deepest injection well, Paradox Valley, Southwest Colorado: Developments in Water Science, v. 52, p. 361-375.

Raleigh, C. B., J.H. Healy, and J. D. Bredehoeft, 1972, Earthquakes and fluid injection: Experiment in earthquake control at Rangely, Colorado, in AAPG Memoir 18, AAPG Special Volumes: Tulsa, American Association of Petroleum Geologists.

Van Poollen, H. K., and D. B. Hoover, 1970, Waste Disposal and Earthquakes at the Rocky Mountain Arsenal, Derby, Colorado: SPE 2558, Journal of Petroleum Technology, August 1970, Pages 983-993.

Wong, I. G. and R. G. Smith, 1981, Low-Level Historical and Contemporary Seismicity in the Paradox Basin, Utah and its Tectonic Implications: Rocky Mountain Association of Geologists 1981 Conference, p. 169-185.

Oklahoma

Cole, J. G., 1970, Marmaton Group East Flank of the Nemaha Ridge: The Shale Shaker Digest VII, p. 67-82.

Holland, A. A., 2011, Examination of Possibly Induced Seismicity from Hydraulic Fracturing in the Eola Field, Garvin County, Oklahoma: Oklahoma Geological Survey Open-File Report, OF1-2011, (OGS website).

Holland, A. A., 2013, Earthquakes Triggered by Hydraulic Fracturing in South-Central Oklahoma: Bulletin of the Seismological Society of America, v. 103, p. 1784-1792, doi:10.1785/0120120109.

Holland, A. A. and A. R. Gibson, Analysis of the Jones, Oklahoma, Earthquake Swarm: Seismological Society of America 2011 Conference, Poster n. 41, (OGS website).

Holland, A. A., C. R. Toth, and E. M. Baker, 2013, Probabilistic Seismic Hazard Assessment and Observed Ground Motions for the Arcadia, Oklahoma, Dam Site: Oklahoma Geological Survey Special Publication, SP2013-01, 63 p., (OGS website).

Joseph, L., 1987, Subsurface Analysis, "Cherokee" Group (Des Monesian), Portions of Lincoln, Pottawatomie, Seminole, and Okfuskee Counties, Oklahoma: The Shale Shaker, v. 36-39, p. 44-69.

Keller, G. R., H. Al-Refaee, and L. Guo, 2012, New Results on the Structure and Evolution of Some Major Structures in the Central U. S.: Seismological Society of America 2012 Conference, abstract, (http://www.seismosoc.org/meetings/2012/app/)

Kernanen, K. M., H. M. Savage, G. A. Abers and E. S. Cochran, Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence, Geology, G34045.1, first published on March 26, 2013 as doi:10.1130/G34045.1

Pulling, D. M., 1979, Subsurface Stratigraphic and Structural Analysis, Cherokee Group, Pottawatomie County, Oklahoma: The Shale Shaker, Part 1 in v. 29 n. 6, p. 124-137 Part 2 in v. 29, n. 7, p. 148-158.

Toth, C.R., Holland, A.A., Keller, G.R. & Holloway, S.D., 2012. P and S Travel Time Tomography Using a Dense Array of Portable Seismographs and Earthquake Sources in Central Oklahoma, presented at 2012 Fall Meeting, AGU, (OGS website).

Toth, C., A. Holland, K. Keranen, and A. Gibson, 2012, Relocation and Comparison of the 2010 M4.1 and 2011 M5.6 Earthquake Sequences in Lincoln County, Oklahoma: Seismological Society of America 2012 Conference, Poster n. 46, (http://www.seismosoc.org/meetings/2012/app/).

PRODUCTION CASE STUDIES

Belayneh, M., S. K. Matthäi and J. W. Cosgrove, 2007, Implications of fracture swarms in the Chalk of SE England on the tectonic history of the basin and their impact on fluid flow in high-porosity, low-permeability rocks, *in* Ries, A. C., R. W. H. Butler, and R. H. Graham, ed., Deformation of the Continental Crust: The Legacy of Mike Coward: Special Publications: London, The Geological Society of London, p. 499-517.

Dahm, T., S. Hainzl, D. Becker, and FKPE group DINSeis, 2007, 2004 Mw 4.4 Rotenburg, Northern Germany, earthquake and its possible relationship with gas recovery: Bulletin of the Seismological Society of America, v. 97, no. 3, p. 691-704.

Doser, D. I., M. R. Baker and D. B. Mason, 1991, Seismicity in the War-Wink gas field, Delaware Basin, west Texas, and its relationship to petroleum production: Bulletin of the Seismological Society of America, v. 81, no. 3, p. 971-986.

Dubos-Sallee, N., T. Bardainne and G. Sénéchal, 2006, Lacq gas field seismicity: Spatio-temporal evolution over 30 years: Geophysical Research Abstracts, v. 8, no. 03299, p. 2.

Grasso, J.-R., and G. Wittlinger, 1990, Ten years of seismic monitoring over a gas field: Bulletin of the Seismological Society of America, v. 80, no. 2, p. 450-473.

Mereu, R. F., J. Brunet, K. Morrissey, B. Price and A. Yapp, 1986, A study of the microearthquakes of the Gobles oil field area of Southwestern Ontario: Bulletin of the Seismological Society of America, v. 76, no. 5, p. 1215-1223.

Ottemoller, L., H. H. Nielsen, K. Atakan, J. Braunmiller, and J. Havskov, 2005, 7 May 2001 induced seismic event in the Ekofisk oil field, North Sea: Journal of Geophysical Research, v. 110, no. B10301, p. 1-15.

Segall, P., J-R.Grasso and A. Mossap, 1994, Poroelastic stressing and induced seismicity near the Lacq gas field, Southwestern France: Journal of Geophysical Research, v. 99, p. 15423-15438.

Van Eck, T., F. Goutbeek, H. Haak and B. Dost, 2006, Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in the Netherlands: Engineering Geology, v. 87, p. 105-121.

Van Eijs, R. M. H. E., F. M. M. Mulders, M. Nepveu, C. J. Kenter, and B. C. Scheffers, 2006, Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands: Engineering Geology, v. 84, p. 99-111.

Zoback, M. D., and J. C. Zinke, 2002, Production-induced normal faulting in the Valhall and Ekofisk Oil Fields: Pure and Applied Geophysics, v. 159, p. 403-420.

NUCLEAR FACILITY SEISMIC CHARACTERIZATION[30]

Budnitz, R. J., G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P.A. Morris, , Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts, NUREG/CR-6372, UCRL-ID-122160, v. 1.

Coppersmith, K. J. etal, 2012, Technical Report: Central and Eastern United States Seismic Source Characterization for Nuclear Facilities. EPRI, Palo Alto, CA, U.S. DOE, and U.S. NRC, NUREG-2115, DOE/NE-0140, EPRI 1-21097, six volumes.

Hanson, K.L., K. I. Nelson, M. A. Angell, and W. R. Lettis, 1999, Techniques for Identifying Faults and Determining Their Origins, NUREG/CR-5503.

U.S. NRC, 2007 revision, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition; Section 2.5.1 Basic Geologic and Seismic Information, NUREG-0800.

PROTOCOLS OR RISK ANALYSIS

2010, Final report and recommendations, Workshop on Induced Seismicity due to Fluid Injection/Production from Energy-Related Applications: Stanford University, Palo Alto, California, Lawrence Berkeley National Laboratory, p. 33.

Bull, J., 2013, Induced Seismicity and the Oil and Gas Industry Oil and Gas Industry: GWPC 2013 Proceedings, Day 2, AXPC.

Dahm, T., D. Becker, M. Bischoff, S. Cesca, B. Dost, R. Fritschen, S. Hainzl, C. D. Klose, D. Kühn, S. Lasocki, Th. Meier, M. Ohrnberger, E. Rivalta, U. Wegler, and S. Husen, 2013, Recommendation for the discrimination of human-related and natural seismicity: Journal of Seismology, v. 17, p. 197–202, DOI 10.1007/s10950-012-9295-6.

Dahm, T., S. Hainzl, D. Becker, and FKPE group DINSeis, 2010, How to discriminate induced, triggered and natural seismicity, *in* Proceedings of the ECGS - FKPE Workshop on Induced Seismicity, Luxembourg.

Dellinger, P., 2011, EPA actions on induced seismicity, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas, US Environmental Protection Agency.

Hunt, S. P., and C. P. Morelli, 2006, Cooper Basin HDR seismic hazard evaluation: Predictive modelling of local stress changes due to HFR geothermal energy operations in South Australia, *in* Adelaide, U. o., ed., South Australian Department of Primary Industries and Resources, Government of South Australia

[30] NUREG publications at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/
NUREG/CR publications at http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/

Johnson, D., 2011, Regulatory response to induced seismicity in Texas, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas, Texas Railroad Commission.

Majer, E., 2011, Induced seismicity associated with energy applications: Issues, status, challenges, needs, technology, Presentation to National Academy of Science: Lawrence Berkeley National Laboratory, Berkeley, California.

Passarelli, L., E. Rivalta, and E. A. Boku, A probabilistic approach for the classification of earthquakes as 'triggered' or 'not triggered': Journal of Seismology, v. 17, p. 165-187.

Petersen, M. D., et al, 2008, Documentation for the 2008 Update of the United States National Seismic Hazard Maps, USGS Open-File Report 2008-1128.

Younan, A., 2013, Technical Elements to Consider in a Risk Management Framework for Induced Seismicity: GWPC 2013 Proceedings, Day 2.

Zoback, M., Kitasei, S., and Copithoren, B., 2010, Addressing the Environmental Risks from Shale Gas Development, Worldwatch Institute, 19 pp, <http://www.worldwatch.org/files/pdf/Hydraulic%20Fracturing%20Paper.pdf>

Zoback, M., 2012, Managing the Seismic Risk Posed by Wastewater Disposal, in Earth April 2012, Pages 38-43.

Sequestration of CO_2

Aschehoug, M. and C. S. Kabir, 2011, Real-Time Evaluation of CO_2, Production and Sequestration in a Gas Field.

Cappa, F. and J. Rutqvist, 2011, Impact of CO2 geological sequestration on the nucleation of earthquakes: Geophysical Research Letters, v. 38, L17313, (http://onlinelibrary.wiley.com/doi/10.1029/2011GL048487/pdf).

Ehlig-Economides, C. and M. J. Economides, 2010, Sequestering carbon dioxide in a closed underground volume, Journal of Petroleum Science and Engineering, v. 70, p. 123–130.

Evans, K. F., A. Zappone, T. Kraft, N. Deichmann and F. Moia, 2012, A survey of the induced seismic responses to fluid injection in geothermal and CO2 reservoirs in Europe: Geothermics, v. 41, January 2012, p. 30-54.

Finley, R. J., 2011, Approaches to assessing induced seismicity at a geological sequestration test in a deep saline reservoir, Decatur, Illinois: Presentation to National Academy of Science, University of Illinois.

Guthrie, G. 2011, Understanding the risks and benefits of induced seismicity through DOE's CCS field project: Presentation for National Academy of Science, US Department of Energy.

Jeanne, P., Y. Guglielmi and F. Cappa, 2013, Dissimilar properties within a carbonate-reservoir's small fault zone, and their impact on the pressurization and leakage associated with CO2 injection: Journal of Structural Geology, v. 47, February 2013, p. 25-35.

Juanes, R., B. H. Hager, and H. J. Herzog, 2012, No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful: PNAS, v. 109, n.52, p. E3623; published ahead of print, doi:10.1073/pnas.1215026109.

Lucier, A., M. Zoback, N. Gupta, T. S. Ramakrishnan, 2006, Geomechanical aspects of CO_2 sequestration in a deep saline reservoir in the Ohio River Valley region: Environmental Geosciences, v. 13, no. 2, p. 85-103.

Mazzoldi, A., A. P. Rinaldi, A. Borgia, and J. Rutqvist, 2012, Induced seismicity within geological carbon sequestration projects: Maximum earthquake magnitude and leakage potential from undetected faults: International Journal of Greenhouse Gas Control v. 10, p. 434–442.

Melzer, S., 2011, CO2 enhanced oil recovery (tertiary production) with some comments on risk sequestration monitoring, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas.

Myer, L. R., and T. M. Daley, 2011, Elements of a best practices approach to induced seismicity in geologic storage: Energy Procedia, v. 4, p. 3707-3713.

Rinaldi, A. P. and J. Rutqvist, 2013, Modeling of deep fracture zone opening and transient ground surface uplift at KB-502 CO2 injection well, In Salah, Algeria: International Journal of Greenhouse Gas Control, v. 12, p. 155–167.

Shi, J-Q., C. Sinayuc, S. Durucan and A. Korre, 2012, Assessment of carbon dioxide plume behaviour within the storage reservoir and the lower caprock around the KB-502 injection well at In Salah: International Journal of Greenhouse Gas Control, v. 12, p. 115-126.

Sminchak, J. and N. Gupta, Aspects of induced seismic activity and deep-well sequestration of carbon dioxide: Environmental Geosciences, June 2003, v. 10, p. 81-89, doi:10.1306/eg.04040302009.

Verdon, J. P., J-M. Kendall and S. C. Maxwell, 2010, Comparison of passive seismic monitoring of fracture stimulation from water and CO_2 injection: Geophysics, v. 75, p. MA1-MA7.

Zoback, M. D. and S. M. Gorelick, Earthquake triggering and large-scale geologic storage of carbon dioxide: PNAS v. 109, n. 26, p. 10164-10168; published ahead of print June 18, 2012, doi:10.1073/pnas.1202473109.

Zoback, M. D. and S. M. Gorelick, Reply to Juanes et al.: Evidence that earthquake triggering could render long-term carbon storage unsuccessful in many regions: PNAS v. 109, n. 52, p. E3624; published ahead of print December 7, 2012, doi:10.1073/pnas.1217264109.

Technical or Technology

Agarwal, R. G., 1980, A new method to account for producing time effects when drawdown type curves are used to analyze pressure buildup and other test data, Document ID 9289-MS, Society of Petroleum Engineers Annual Technical Conference and Exhibition: Dallas, Texas, Society of Petroleum Engineers, p. 20.

Baisch, S., and R. Voros, 2010, Reservoir induced seismicity: Where, when, why and how strong?, Paper # 3160, *in* World Geothermal Congress, Bali, Indonesia.

Bourdet, D., J. A. Ayoub and Y. M. Pirard, 1989, Use of pressure derivative in well-test interpretation, Document ID 12777-PA: SPE Formation Evaluation, v. 4, no. 2, p. 293-302.

Bourdet, D., T. M. Whittie, A. A. Douglas and Y. M. Pirard, 1983, A new set of type curves simplifies well test analysis: World Oil (May 1983), p. 7.

Bradley, J. S. and D. E. Powley, 1994, Pressure compartments in sedimentary basins: a review: in Ortoleva, P. J. (ed.) Basin compartments and Seals: American Association of Petroleum Geologists Memoir 61, p. 3-26.

Cinco-Ley, H., 1996, Reservoir Models for NFR, *in* Transient Well Testing, Kamal, 2009.

Constant, W. D., and A. T. Bourgoyne, 1988, Fracture gradient prediction for offshore wells, Document ID 15105-PA: SPE Drilling Engineering, v. 3, no. 2, p. 136-140.

Daley, T. M., R. Haught, J. E. Peterson, K. Boyle, J. H. Beyer and L. R. Hutchings, 2010, Seismicity characterization and monitoring at WESTCARB's proposed Montezuma Hills geologic sequestration site: Lawrence Berkeley National Laboratory.

Deflandre, J.-P., S. Vidal-Gilbert and C. Wittrisch, 2004, Improvements in downhole equipment for fluid injection and hydraulic fracturing monitoring using associated induced seismicity, Document ID 88787-MS, Abu Dhabi International Conference and Exhibition: Abu Dhabi, United Arab Emirates, Society of Petroleum Engineers, p. 7.

Eaton, B. A., 1969, Fracture gradient prediction and its application in oilfield operations, Document ID 2163-PA: Journal of Petroleum Technology, v. 21, no. 10, p. 1353-1360.

Eaton, B. A., 1975, The equation for geopressure prediction from well logs, Document ID 5544-MS, Fall Meeting of the Society of Petroleum Engineers of AIME: Dallas, Texas, Society of Petroleum Engineers, p. 11.

Ehlig-Economides, C. A., P. Hegeman and G. Clark, 1994, Three key elements necessary for successful testing: Oil and Gas Journal, v. 92, p. 84-93.

Ehlig-Economides, C. A., P. Hegeman and S. Vik, 1994, Guidelines simplify well test interpretation: Oil and Gas Journal, v. 92, p. 33-39.

Felsenthal, M., 1974, Step rate tests determine safe injection pressures in floods: Oil and Gas Journal, v. 72, p. 49-54.

Hall, H. N., 1963, How to analyze waterflood injection well performance: World Oil, October 1963, p 128-130.

Hearn, C. L., 1983, Method analyzes injection well pressure and rate data: Oil and Gas Journal, v. 81, p. 117-120.

Hennings, P., 2009, AAPG - SPE - SEG Hedburg research conference on "the geologic occurrence and hydraulic significant of fractures in reservoirs": AAPG Bulletin, v. 93, no. 11, p. 1407-1412.

Izgec, B., and C. S. Kabir, 2009, Real-time performance analysis of water-injection wells: SPE Reservoir Evaluation & Engineering, v. 12, no. 1, p. 116-123.

Izgec, B., and C. S. Kabir, 2011, Identification and Characterization of High-Conductive Layers in Waterfloods: SPE Reservoir Evaluation & Engineering, v. 14, n. 1, p. 113-119.

Jarrell, P. M., and M. H. Stein, 1991, Maximizing injection rates in wells recently converted to injection using Hearn and Hall plots, Document ID 21724-MS, Society of Petroleum Engineers Production Operations Symposium: Oklahoma City, Oklahoma, Society of Petroleum Engineers.

Kabir, C. S., and B. Izgec, 2010, Identification and characterization of high-conductive layers in waterfloods, Document ID 123930, SPE Annual Technical conference and Exhibition: New Orleans, Louisiana, Society of Petroleum Engineers, p. 15.

Kamal, M. M., 2009, Transient well testing: Monograph 23, Society of Petroleum Engineers, p. 850.

Latham, J-P., J. Xiang, M. Belayneh, H. M. Nick, C0F. Tsang, and M. J. Blunt, 2013, Modelling stress-dependent permeability in fractured rock including effects of propagating and bending fractures: International Journal of Rock Mechanics and Mining Sciences, v. 57, January 2013, p. 100-112.

Lee, C. C., and S. D. Lin, 1999, Handbook of environmental engineering calculations: McGraw-Hill Professional, p. 1278-1280.

Lee, J., J. B. Rollin and J. P. Spivey, 2003, Pressure transient testing: SPE Textbook Series, Society of Petroleum Engineers.

Lee, W. J., 1987, Pressure-transient test design in tight gas formations, Document ID 17088-PA: Journal of Petroleum Technology, v. 39, no. 10, p. 1185-1195.

Martakis, N., A. Tselentis and P. Paraskevopoulos, 2011, High resolution passive seismic tomography -- a NEW exploration tool for hydrocarbon investigation, recent results from a successful case history in Albania, Article #40729, Search and Discovery, AAPG/Datapages, Inc.

Matthews, W. R., 1984, How to calculate pore pressures, gradients from well logs for the U. S. West Coast: Oil and Gas Journal, v. 82, p. 132-137.

Narr, W., D. Schechter and L. Thompson, 2006, Naturally Fractured Reservoir Characterization, An Interdisciplinary Approach to Topics in Petroleum Engineering and Geosciences, Society of Petroleum Engineers, 112 p.

Nolte, K. G., J. L. Maniere and K. A. Owens, 1997, After-closure analysis of fracture calibration tests, Document ID 38676-MS, Society of Petroleum Engineers Annual Technical Conference and Exhibition: San Antonio, Texas, Society of Petroleum Engineers, p. 17.

Proano, E. A., and I. J. Lilley, 1986, Derivative of pressure: Application to bounded reservoir interpretation, Document ID 15861-MS, European Petroleum Conference: London, United Kingdom, Society of Petroleum Engineers, p. 12.

Salazar, A., and A. Kumar, 1992, Case histories of step rate tests in injection wells, Document ID 23958, Permian Basin Oil and Gas Recovery Conference: Midland, Texas, Society of Petroleum Engineers, p. 12.

Silin, D. B., R. Holtzman, T. W. Patzek, J. L. Brink, and M. L. Minner, 2005, Waterflood surveillance and control: Incorporation Hall plot and slope analysis, Document ID 95685, Society of Petroleum Engineers 2005 Annual Technical Conference and Exhibition: Dallas, Texas, Society of Petroleum Engineers, p. 15.

Silin, D. B., R. Holtzman, T. W. Patzek, and J. L. Brink, 1992, Monitoring waterflood operations: Hall method revisited, Document ID 93879, Society of Petroleum Engineers Western Regional Meeting: Irvine, California, Society of Petroleum Engineers, p. 12.

Singh, P. K., R.G. Agarwal and L.D. Krase, 1987, Systematic design and analysis of step-rate tests to determine formation parting pressure, Document ID 16798-MS, Society of Petroleum Engineers Annual Technical Conference and Exhibition: Dallas, Texas, Society of Petroleum Engineers, p. 13.

Soliman, M. Y. and C. S. Kabir, 2012, Testing unconventional formations, Journal of Petroleum Science and Engineering, v. 92–93, p. 102–109.

Spivey, J. P., W. B. Ayers Jr.; D. A. Pursell and W. J. Lee, 1997, Selecting a reservoir model for well test interpretation: Petroleum Engineer International (December 1997), p. 83-88.

Spivey, J. P., and Lee, W. J., 1997, Fundamentals of type curve analysis: Petroleum Engineer International (September 1997), p. 63-71.

Spivey, J. P., and Lee, W. J., 1997, Identifying flow regimes in pressure transient tests: Petroleum Engineer International (October 1997), p. 66-70.

Spivey, J. P., and Lee, W. J., 1997, Introduction to applied well test interpretation: Petroleum Engineer International (August 1997), p. 41-46.

Spivey, J. P., and Lee, W. J., 1997, Well test interpretation in bounded reservoirs: Petroleum Engineer International (November 1997), p. 81-89.

Stewart, G., 1997, Recent developments in well test analysis: Petroleum Engineer International (August 1997), p. 47-56.

Tingay, M. R. P., B. Müller, J. Reinecker and O. Heidbach, 2006, State and origin of the present-day stress field in sedimentary basins: New results from the stress map project, ARMA/USRMS 06-1049, Golden Rocks 2006, The 41st US Symposium on Rock Mechanics (USRMS): Golden, Colorado.

Van Poolen, H. K., 1964, Radius-of-drainage and stabilization-time equations: Oil and Gas Journal (September 14, 1964), p. 138-146.

Veneruso, A. F., and L. Petitjean, 1991, Pressure gauge specification considerations in practical well testing, Document ID 22752-MS, Society of Petroleum Engineers Annual Technical Conference and Exhibition: Dallas, Texas, Society of Petroleum Engineers.

Vlastos, S., E. Liu, I. G. Main, M. Schoenberg, C. Narteau, X. Y. Li and B. Maillot, 2006, Dual simulations of fluid flow and seismic wave propagation in fractured network: Effects of pore pressure on seismic signature: Geophysical Journal International, v. 166, p. 825-838.

Yoshida, C., S. Ikeda and B.A. Eaton, 1996, An investigative study of recent technologies used for prediction, detection, and evaluation of abnormal formation pressure and fracture pressure in North and South America, Document ID 36381-MS, Society of Petroleum Engineers/International Association of Drilling Contractors Asia Pacific Drilling Technology Conference: Kuala Lumpur, Malaysia, Society of Petroleum Engineers, p. 21.

Yoshioka, K., B. Izgec and R. Pasikki, 2008, Optimization of Geothermal Well Stimulation Design Using a Geomechanical Reservoir Simulator: PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2008, SGP-TR-185.

FAULT STUDIES

Guglielmi, Y., F. Cappa, and D. Amitrano, 2008, High-definition analysis of fluid-induced seismicity related to the mesoscale hydromechanical properties of a fault zone: Geophysical Research Letters, v. 35, no. 6, p. 1-6.

Hanson, K.L., K. I. Nelson, M. A. Angell, and W. R. Lettis, 1999, Techniques for Identifying Faults and Determining Their Origins, NUREG/CR-5503.

Jeanne, P., Y. Guglielmi and F. Cappa, 2013, Dissimilar properties within a carbonate-reservoir's small fault zone, and their impact on the pressurization and leakage associated with CO2 injection: Journal of Structural Geology, v. 47, February 2013, p. 25-35.

Juanes, R., B. H. Hager, and H. J. Herzog, 2012, No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful: PNAS 2012, v. 109, (52) E3623; published ahead of print, doi:10.1073/pnas.1215026109.

Mitchell, T. M. and D. R. Faulkner, 2012, Towards quantifying the matrix permeability of fault damage zones in low porosity rocks: Earth and Planetary Science Letters, v. 339–340, 15 July 2012, p. 24-31.

Sibson, R. H., 1994, Crustal Stress, Faulting and Fluid Flow: Geological Society Special Publication, v. 78, 1, p. 69-84.

Townend, J., and M. D. Zoback, 2000, How faulting keeps the crust strong: Geology, v. 28, n. 5, p. 399-402, doi:10.1130/0091-7613(2000)028<0399:HFKTCS>2.3.CO;2.

USGS, 2004, Quaternary Fault and Fold Database for the Nation: USGS Fact Sheet 2004-3033, 2 p.

Wiprut, D., and Zoback, M. D., Fault reactivation, leakage potential, and hydrocarbon column heights in the northern north sea, in Norwegian Petroleum Society Special Publications, Volume 11, 2002, Pages 203–219, <http://dx.doi.org/10.1016/S0928-8937(02)80016-9, How to Cite or Link Using DOI>.

HYDRAULIC FRACTURING OR MICROSEISMICITY

Arthur, J. D., and Coughlin, B. J., 2008, Hydraulic fracturing considerations for natural gas wells of the Fayetteville Shale, Presented at the Ground Water Protection Council 2008 Annual Forum: Cincinnati, Ohio.

BC Oil and Gas Commission, 2012, Investigation of Observed Seismicity in the Horn River Basin: BC Oil and Gas Commission, 29 pp.

Daneshy, A., 2013, Oil & Gas Operations & Formation Failure: (http://gen.usc.edu/assets/001/81096.pdf)

Das, I., and Zoback, M. D., 2011, Long period long duration seismic events during hydraulic stimulation of a shale gas reservoir, Article #40761, Search and Discovery, AAPG/Datapages, Inc.

de Pater, C. J., and S. Baisch, 2011, Geomechanical study of Bowland Shale seismicity synthesis report: Cuadrilla Resources.

Eisner, L., V. Grechka, and S. Williams-Stroud, 2011, Future of microseismic analysis: Integration of monitoring and reservoir simulation, Article #40784, Search and Discovery, AAPG/Datapages, Inc.

Fehler, M., L. House and H. Kaieda, 1986, Seismic Monitoring of Hydraulic Fracturing: Techniques for Determining Fluid Flow Paths and State of Stress Away From a Wellbore, 27th U.S. Symposium on Rock Mechanics (USRMS), June 23 - 25, 1986 , Tuscaloosa, AL.

Fisher, K., and N. Warpinski, 2011, Hydraulic Fracture-Height Growth: Real Data. SPE Paper 145949, p. 18.

Fischer, T., and A. Guest, 2011, Shear and tensile earthquakes caused by fluid injection: Geophysical Research Letters, v. 38, p. 4.

Friedmann, S., 2012, The future (and promise) of fracking technology: US Energy Association, Washington, Lawrence Livermore National Laboratory, (http://www.usea.org/Publications/USEA_ShaleGasTech_Jan2012.pdf)

Gidley, J. L., S. A. Holditch, D. E. Nierode, and R. W. Veatch, Jr., editors, 1989, Recent advances in hydraulic fracturing, SPE Monograph Series Volume 12, Society of Petroleum Engineers, p. 464.

Hnat, J., A. Reynolds, W. Langin, J. Le Calvez, and J. Tan, 2013, Assessing the Impact of Recording Geometry on Microseismic Data: An Example from the Marcellus, AAPG ACE 2013 – Pittsburgh, PA, 16 p.

Holland, A., 2011, Examination of possibly induced seismicity from hydraulic fracturing in the Eola Field, Garvin County, Oklahoma, Oklahoma Geological Survey, Open-File Report OF1-2011.

Holland, A. A., 2013, Earthquakes Triggered by Hydraulic Fracturing in South-Central Oklahoma: Bulletin of the Seismological Society of America, v. 103, p. 1784-1792.

Hurd, O. and M. D. Zoback, 2012, Intraplate earthquakes, regional stress and fault mechanics in the Central and Eastern U.S. and Southeastern Canada, Tectonophysics, V. 581, 18 December 2012, p. 182-192.

Kanamori, H. and E. Haukksson, 1992, A Slow Earthquake in the Santa Maria Basin, California: Bulletin of the Seismological Society of America, v. 82, n. 5, p. 2087-2096.

King, G.E., 2012, Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells, SPE 152596.

Maxwell, S., 2011, Imaging hydraulic fractures using induced microseismicity, *in* National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies, Dallas, Texas.

Maxwell, S., 2011, What Does Microseismicity Tells Us About Hydraulic Fractures?, 2011 SEG Annual Meeting, September 18 - 23, 2011 , San Antonio, Texas, 5 pp.

Phillips, W. S., J. T. Rutledge, L. S. House and M. C. Fehler, 2002, Induced microearthquake patterns in hydrocarbon and geothermal reservoirs: Six case studies: Pure and Applied Geophysics, v. 159, no. 1-3, p. 345-369.

Vermylen, J., and M. D. Zoback, Hydraulic fracturing, microseismic magnitudes and stress evolution in the Barnett Shale, Texas, USA, SPE 140507, SPE Hydraulic Fracturing Technology Conference and Exhibition, held in The Woodlands, Texas, USA 24-26, January 2011.

Warpinski, N., 2009, Microseismic monitoring: Inside and out: Journal of Petroleum Technology, v. 61, no. 11, p. 80-85.

Warpinski, N., J. Du and U. Zimmer, 2012, Measurements of Hydraulic-Fracture-Induced Seismicity in Gas Shales: SPE 151597 presented at the Society of Petroleum Engineers Hydraulic Fracturing Technology Conference, The Woodlands, Texas, 6-8 February.

Seismic Monitoring

Braile, L. W., and S. J. Braile, 2002, Introduction to SeisVolE teaching modules: Lessons, activities and demonstrations using the SeisVolE earthquake and volcanic eruption mapping software, Purdue University, Accessed November 22, 1011 (http://web.ics.purdue.edu/~braile/edumod/svintro/svintro.htm), Last updated February 4, 2002.

Häge, M., P. Blascheck, and M. Joswig, 2013, EGS hydraulic stimulation monitoring by surface arrays - location accuracy and completeness magnitude: the Basel Deep Heat Mining Project case study: Journal of Seismology, v. 17, p. 51-61.

Kraaijpoel, D. and B. Dost, Implications of salt-related propagation and mode conversion effects on the analysis of induced seismicity: Journal of Seismology, v. 17, p. 95-107.

Kwee, J., D. Kraaijpoel, and B. Dost, 2010, Microseismic pilot study in the Bergermeer Field: Summary of results: Royal Netherlands Meterological Institute, Department of Seismology.

Lockridge, J. S., M. J. Fouch, and J. R. Arrowsmith, 2012, Seismicity within Arizona during the Deployment of the EarthScope USArray Transportable Array: Bulletin of the Seismological Society of America, v. 102, n. 4, p. 1850–1863.

Salas, C. J., D. Walker, and H. Kao, 2013, Creating a Regional Seismograph Network in Northeastern British Columbia to Study the Effect of Induced Seismicity from Unconventional Gas Completions: Geoscience BC Report 2013-1, p. 131-133.

Shemeta, J., B. Goodway, M. Wiilis and W. Heigl, 2012, An introduction to this special section: Passive seismic and microseismic—Part 2, The Leading Edge December 2012, p. 1428-1435.

SELECTED SEISMOLOGY ARTICLES

Eisner, L., B. J. Hulsey, P. Duncan, D. Jurick, H. Werner and W. Keller, 2010, Comparison of surface and borehole locations of induced seismicity: Geophysical Prospecting, v. 58, p. 809–820.

Hurd, O. and M. D. Zoback, 2012, Intraplate earthquakes, regional stress and fault mechanics in the Central and Eastern U.S. and Southeastern Canada, Tectonophysics, V. 581, 18 December 2012, p. 182-192.

Klose, C., 2012, Mechanical and statistical evidence of the causality of human-made mass shifts on the Earth's upper crust and the occurrence of earthquakes:

Klose, C. and L. Seeber, 2007, Shallow seismicity in stable continental regions: Seismological Research Letters, v. 78, n. 5, p. 554-562.

Lacazette, A., S. Fereja, C> Sicking, J. Vermiye, P. Geiser and L. Thompson, 2013, Imaging Fracture Networks with Ambient Seismicity, AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22.

McGarr, A., 1976, Seismic Moments and Volume Changes: Journal of Geophysical Research, v. 81, n. 8, p. 1487-1494.

Monnin, M. M. and J. L. Seidel, 1992, Radon in soil-air and in groundwater related to major geophysical events: A survey, v. 314, Issue 2, 15 April 1992, p. 316-330.

Montési, L. G. and M. T. Zuber, 2002, A Unified Description of Localization for Application To Large-Scale Tectonics, Journal of Geophysical Research, v. 107, B3.

Murray, J. and P. Segall, 2002, Testing time-predictable earthquake recurrence by direct measurement of strain accumulation and release: Nature, V. 419, September 2002, p. 287-291.

WELLS AND ROCK MECHANICS[31]

Brace, W. F. and D. L, Kohlstedt, 1980, Limits on lithospheric stress imposed by laboratory experiments, Journal of Geophysical Research, v. 85, p. 6248–6252.

Beeler, N. M., R. W. Simpson, S. H. Hickman and D.A. Lockner, 2000, Pore Fluid Pressure, Apparent Friction, and Coulomb Failure: Journal of Geophysical Research, v. 105, B11, p. 25,533-25,542.

Boullier, A-M., 2011, Fault-zone geology: lessons from drilling through the Nojima and Chelunga faults: from A˚. Fagereng, V. G. Toy, J. V. & Rowland, (eds) Geology of the Earthquake Source: A Volume in Honour of Rick Sibson. Geological Society, London, Special Publications, 359, 17–37. DOI: 10.1144/SP359.2 0305-8719/11/$15.00 # The Geological Society of London 2011. (http://sp.lyellcollection.org/).

Brudy, M., M. D. Zoback, K. Fuchs, F. Rummel, and J. Baumgartner, 1997, Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes—Implications for crustal strength: Journal of Geophysical Research, v. 102, p. 18453–18475.

Bruno, M. S., 1990, Subsidence-Induced Well Failure: SPE 20058.

Cook, J., et al., 2007, Rocks Matter: Ground Truth in Geomechanics: Schlumberger Oilfield Review, v. 19, p. 36-55, (http://www.slb.com/resources/publications/industry_articles/oilfield_review/2007/or2007aut03_rocks_matter.aspx).

Cornet, F. H., 2012, The relationship between seismic and aseismic motions induced by forced fluid injections, Hydrogeology Journal, v. 20, p. 1463–1466.

Davis, S. D. and W. D. Pennington, 1989, Induced Seismic Deformation in the Cogdell Oil field of West Texas, Bulletin of the Seismological Society of America, v. 79, no. 5, p. 1477-1494.

Dusseault, M. B., 2001, Casing Shear: Causes, Cases, Cures: SPE Drilling & Completion V. 16, No. 2, p. 98-107.

Fischer, T., and A. Guest, 2011, Shear and tensile earthquakes caused by fluid injection: Geophysical Research Letters, v. 38, p. 4.

Fjær, E., et. al., 2008, Petroleum Related Rock Mechanics, 2nd Edition: (http://science.uwaterloo.ca/~mauriced/earth437/Fjaer_et%20al_2008_Petroleum%20Related%20Rock%20Mechanics,%202nd%20Ed.pdf), Elsevier B. V.

Hair, T., H. Alsleben, M. Enderlin and N. Donovan, 2012, Constructing a Geomechanical Model of the Woodford Shale, Cherokee Platform, Oklahoma, USA: Effects of Confining Stress and Rock Strength on Fluid Flow, Search and Discovery Article #50716.

[31] Only a partial list, this is an extensive field.

Hardebeck, J. L., and A. J. Michael, 2006, Damped regional-scale stress inversions—Methodology and examples for southern California and the Coalinga aftershock sequence: Journal of Geophysical Research, v. 111, B11310.

Hosseini, S. M. and F. Javadpour, 2013, Geomechanical Considerations in Seismicity Based Reservoir Characterization, SPE Unconventional Resources Conference - USA, Apr 10 - 12, 2013, SPE 164551-MS.

Hudson, J. A. and J. P. Harrison, 1997, Engineering rock mechanics an introduction to the principles: (http://187.141.81.212/biblioteca/LibrosMaquinas/HUDSON,%20J.%20A.%20(2000).%20Engineering%20Rock%20Mechanics%20(2%20vols.)/Part%201%20-%20An%20Introduction%20to%20the%20Principles/Engineering_Rock_Mechanics_VOLUME1.pdf), Elsevier Science Ltd.

Miller, C., J. E. Clark, D. K. Sparks, and R. W. Nopper, Jr., draft of Review of Failure Criteria and Methodology for Assessing Induced Seismicity Potential of Underground Injection Operations: p. 68.

Perkins, T. K. and J. A. Gonzalez, 1984, Changes in Earth Stresses Around a Wellbore Caused by Radially Symmetrical Pressure and Temperature Gradients: , SPEJ April 1984, pp 129-140.

Pratt, H.R., W.A. Hustrulid, and D.E. Stephenson, 1978, Earthquake Damage to Underground Facilities: (http://www.osti.gov/bridge/servlets/purl/6441638-rVIa3Q/6441638.pdf), p. 36-41.

Reasenberg, P. A., and R. W. Simpson, 1992, Response of regional seismicity to the static stress change produced by the Loma Prieta earthquake: Science, v. 255, p. 1687–1690.

Rice, J. R., 2005, Structure of Mature Faults and Physics of Their Weakening During Earthquakes: KITP Friction, Fracture and Earthquake Physics Conf., Santa Barbara, 15-19 Aug 2005.

Roberts, D. L., E. B. Hall and Co., 1953, Shear Prevention in the Wilmington Field, Drilling and Production Practice: American Petroleum Institute.

Schmitt, D. R., C. A. Currie, and L. Zhang, 2012, Crustal stress determination from boreholes and rock cores: Fundamental principles; Tectonophysics, v. 580, 10 December 2012, p. 1-26.

Scholz C. H., 2002, The Mechanics of Earthquakes and Faulting, 2nd edn. New York: Cambridge Univ. Press; p. 471.

Shalev, E. and V. Lyakhovsky, 2013, The processes controlling damage zone propagation induced by wellbore fluid injection: Geophysical Journal International, doi: 10.1093/gji/ggt002.

Shaw, R. P., 2005, Overview of the NERC 'Understanding the Micro to Macro Behaviour of Rock-Fluid Systems': Geological Society, London, Special Publications 2005, v. 249, p. 145-161.

Soliman, M.Y., Miranda, C., and Wang, H.M., 2010, Application of After-Closure Analysis to a Dual-Porosity Formation, to CBM, and to a Fractured Horizontal Well: SPEPO 25 (4): 472-483.

Stover, C.W. and J.L. Coffman, 1993, Seismicity of the United States, 1568-1989 (revised): USGS Professional Paper 1527, (http://pubs.usgs.gov/pp/1527/report.pdf).

Turuntaev, S. B., E. I. Eremeeva, and E. V. Zenchenko, 2013, Laboratory study of microseismicity spreading due to pore pressure change: Journal of Seismology, v. 17, p. 137-145.

Zang, A. H. W. and O. J. Stephansson, 2008, Measuring Crustal Stress: Borehole Methods: in Stress Field of the Earth's Crust: Springer e-book, p. 131-163, (http://link.springer.com/book/10.1007/978-1-4020-8444-7/page/1).

Zoback, M. D., C. Barton, M. Brudy, D. Castillo, T. Finkbeiner, B. Grollimund, D. Moos, P. Peska, C. Ward, and D. Wiprut, 2003, Determination of stress orientation and magnitude in deep wells: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 40, p. 1049–1076.

Zoback, M. D., J. Townend and B. Grollimund, 2002, Steady-State Failure Equilibrium and Deformation of Intraplate Lithosphere: International Geology Review, v. 44, p. 383–401.

APPENDIX L: DATABASE INFORMATION

CATALOGS OF EARTHQUAKE EVENTS

The largest U.S. database of earthquake events is maintained by the Advanced National Seismic System (ANSS). The National Earthquake Information Center (NEIC) maintains several other data catalogs. Both ANSS and NEIC programs are under the USGS. There is limited consistency between the various groups on coverage areas, detection thresholds, or magnitude determinations. Table L-2 provides a reference to the primary earthquake catalogs. State Geologic Agencies and universities may also collect and/or host earthquake information on their website. The catalogs generally include an indication of the event location reliability. The main ANSS composite catalog, hosted by the Northern California Earthquake Center at Berkeley, contains events from multiple sources and time periods, but strips duplicate listings.

As an example of catalog coverage, the following table shows the number of events recorded in the search area of the Central Arkansas Area Case Study (discussed in detail elsewhere in this report). Care must be taken to avoid duplication when using multiple sources of data. Not all matching events have the same calculated epicenter and depth. It is also noted that depth refinements to preliminary NEIC data, have been incorporated in the ANSS catalog, but not in the NEIC PDE catalog.

TABLE L-1: EARTHQUAKE CATALOG EVENTS FOR CENTRAL ARKANSAS CASE STUDY

Catalog	Common Events with ANSS	Unique Catalog Events	Total Events
ANSS: Central and Eastern US	-	1533	1533
NEIC: SRA[32]	0	0	0
National Center for Earthquake Engineering Research (NCEER)	15	1	16
NEIC: USHIS[33]	1	0	1
Center for Earthquake Research and Information (CERI)	1523	4	1527
NEIC: PDE & PDE-Q	267	12	279
Total unique AR events		1549	

[32] Eastern, Central and Mountain States of U.S. (1350-1986)
[33] Significant U.S. Earthquakes (1568-1989)

TABLE L-2: EARTHQUAKE CATALOGS

Source	Coverage (Years)	Area	Comments/Caveats
International Seismological Centre[34]	1904- present	The official world catalog	Requires an access fee
ANSS Catalog[35] (hosted by NCEDC)	1898 - present	Composite across the USA	M1 and greater
CERI Catalog AKA New Madrid Earthquake Catalog[36]	1974 - present	New Madrid Seismic Zone and surrounding regions	
NEIC (USGS) Catalog[37]	SRA: 1350-1986	Eastern, Central & Mountain States	Very few magnitudes given
	USHIS: 1568-1989	Significant US quakes	Felt or M4.5 and greater
	PDE: 1973- present	USA	Updated file from PDE-Q
	PDE-Q: 1973- present	USA (most recent)	Very preliminary locations
	Real Time: Last 7 days	USA	>= M1; interactive map locations ; with accuracy range
	Alert: current	USA and World	E-mail notification available
NCEER Catalog[38]	1627 - 1985	Central and Eastern United States	Used in national hazard map creation
ANF/ANFR[39]	2009 - present	US Array Network	Contains many surface induced events
IRIS[40] SeismiQuery	1960 - present	US & world	USGS and other networks
Harvard CMT Catalog	1976 - present	Global	Tensor calculations for > M5
Northern California Earthquake Data Center (NCEDC)[41]	1910 - 2003 1967 - present	Northern and Central CA; some all of CA or Western USA	
Southern California Earthquake Data Center (SCEDC)[42]	1977 - present	Southern CA	

[34] ISC: http://www.isc.ac.uk/search/bulletin/index.html

[35] ANSS: http://quake.geo.berkeley.edu/cnss/

[36] CERI/New Madrid Catalog: http://www.ceri.memphis.edu/seismic/catalogs/cat_nm.html

[37] NEIC: http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

[38] NCEER: http://www.ceri.memphis.edu/seismic/catalogs/cat_nceer.html

[39] IRIS EarthScope Data: http://www.iris.edu/earthscope/usarray/

[40] IRIS: http://www.iris.edu/SeismiQuery/sq-events.htm & http://www.iris.edu/dms/wilber.htm

[41] NCEDC: http://www.ncedc.org/ncedc/catalog-search.html

[42] NCEDC: http://www.data.scec.org/

APPENDIX M: USGS COLLABORATION

Through an interagency agreement, EPA was able to employ the expertise of USGS staff for this project as outlined in the scope of work[43] below. USGS prepared a report titled, *Evaluate Potential Risks of Seismic Events due to Injection-Well Activities.* The report included a guide on the USGS earthquake hazards and seismic activity maps aimed at non-geophysicists (UIC scientists and engineers). The report also provided USGS insight on the relationship between subsurface stress fields and the likelihood of induced seismicity.

USGS is updating the 2002 study, *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001*[44]. Table M-1 provides a summary of the seismic events reported in ANSS catalog for the greater Raton Basin Area located in southern Colorado and northern New Mexico as shown in Figure M-1. The area has a number of disposal wells used to inject the wastewater from coalbed methane production. The USGS report, to be completed by April 2012, will provide refined locations and interpretation of many of these events.

Commented [A95]: Need to provide an update since date has passed.

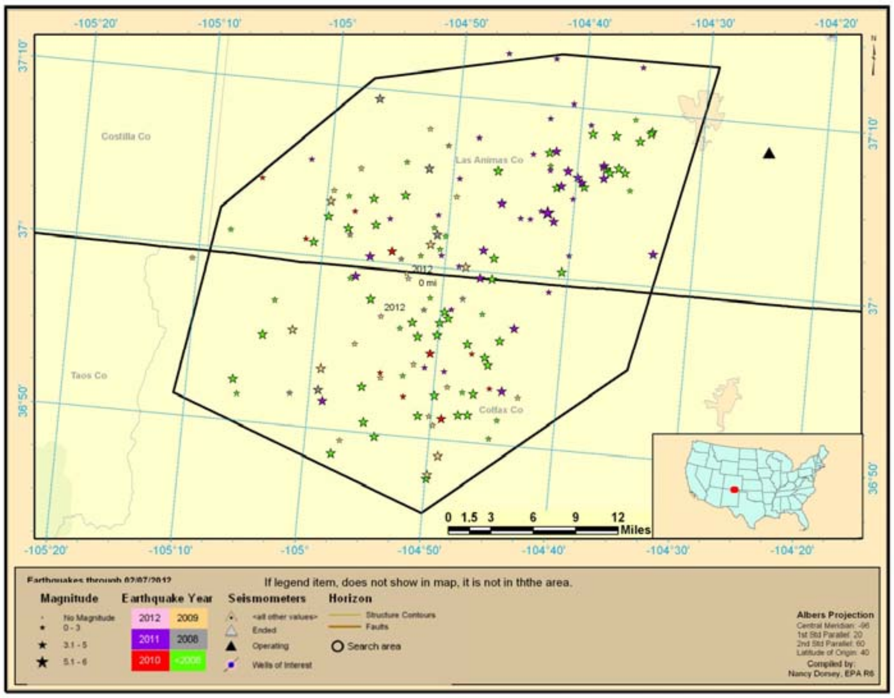
TABLE M-1: SESIMIC EVENTS IN THE RATON BASIN AREA

Year	Starting Date	Number of Events	Min.	Avg.	Max.	Ending Date
1973	9/19/1973	1	0.0	2.1	4.2	9/23/1973
2001	8/28/2001	13	2.8	3.5	4.5	12/15/2001
2002	1/26/2002	4	2.8	3.2	3.5	11/14/2002
2003	4/28/2003	7	2.9	3.4	3.8	11/24/2003
2004	1/14/2004	8	2.9	3.5	4.4	8/1/2004
2005	1/10/2005	10	2.9	3.4	5.0	11/16/2005
2006	1/27/2006	13	2.5	3.0	3.6	12/24/2006
2007	1/3/2007	7	2.6	3.3	4.4	12/17/2007
2008	1/29/2008	10	2.5	2.9	3.4	9/6/2008
2009	2/3/2009	20	2.5	3.0	4.1	12/11/2009
2010	1/18/2010	10	2.5	3.0	3.8	11/10/2010
2011	2/13/2011	40	0.0	3.1	5.4	12/28/2011
2012	1/25/2012	2	2.4	2.5	2.6	1/29/2012

[43] Task 3 was dropped from the scope of work. The timeframe for Task 4 has been extended.

[44] Meremonte, M. E., J. C. Lahr, A. D. Frankel, J. W. Dewey, A. J. Crone, D. E. Overturf, D. L. Carver, and W.T. Bice, 2002, Investigation of an Earthquake Swarm near Trinidad, Colorado, August-October 2001: US Geological Survey Open-File Report 02-0073 [http://pubs.usgs.gov/of/2002/ofr-02-0073/ofr-02-0073.html], accessed December 5, 2011.

FIGURE M-0:A: TRINIDAD AND RATON BASIN SEISMICITY



Scope of Work for USGS and EPA Project on Induced Seismic Activity for Class II Disposal Wells

Objective: Provide support data for EPA's UIC National Technical work group project on induced seismicity from Class II brine disposal well operations.

Background: Numerous publications exist that study the relationship between induced or triggered earthquakes and injection activity. The factors that might influence the occurrence of large damaging earthquakes near Class II disposal wells include (1) large-scale nearby fault(s), (2) high differential stresses at depth, and (3) changes in fluid pressure or stress due to fluid injection. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to enhance strategies for avoiding damaging seismicity events related to Class II disposal wells.

Scope of Work: Through available expertise, complete the following specific work tasks that support the UIC NTW induced seismicity project. USGS and/or procured data will be used and referenced in the UIC NTW final work product. The tasks will necessitate cooperation between EPA and USGS, including incorporating the expertise and experience from EPA UIC geologists and engineers and USGS staff.

Work Tasks

1. Prepare a practical guide on the USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers (non-geophysicists). The document should cover topics such as background information relevant to the two maps, confidence levels and sensitivity of the mapped data. For example:
    a. Describe the epicenter location and hypocentral depth with respect to accuracy of the data. This should include accuracy within both map and depth locations.
    b. Describe the relevance of the earthquake hazard maps for subsurface use.
2. Using technical expertise what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?
3. Incrementally evaluate commercial structure maps on the deepest available horizon for one of the following areas to determine if this type of data can be used as a screening tool. EPA will provide USGS with the structure maps. The evaluation may include, but is not limited to, correlating seismic events and available injection well locations with structural maps. During coordination between EPA and USGS, specific location information will be provided. The following are the generic areas of interest, though EPA may change the priorities.
    a. North Texas Ouachita Thrust front
    b. Arkansas Fayetteville Shale play
    c. West Virginia Braxton County
    d. Colorado Trinidad area
    e. Ashtabula Ohio area

    Depending on the results of the initial pilot study, additional analyses may be performed on more of these areas at a later date.

4. Review *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001* and submit a progress report and final report on updates to this study including identifiers that could have predicted the recent 5.3 earthquake.
5. Provide interim data, final report of conclusions and all work completed.

Milestones

Provide monthly updates

Timeframe

Work and accompanying reports for tasks 1-3 should be completed by December 16, 2011.

A progress report for task 4 should be completed by December 31, 2011, with work on task 4 continuing into 2012. The final report for task 4 should be completed no later than April 30, 2012.

Underground Injection Control Interagency Agreement
EPA IA DW-14-95809701-0

Evaluate Potential Risks of Seismic Events due to Injection-Well Activities

A. McGarr, W. Ellsworth, J. Rubinstein, S. Hickman, E. Roeloffs, and D. Oppenheimer

United States Geological Survey

The Scope of Work for the USGS and EPA project on induced seismic activity for Class II disposal wells includes two tasks:
Task 1—Prepare a practical guide on USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers.
Task 2—Using technical expertise, what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?

The results of USGS work on these two tasks are described in this report.

Task 1.
USGS Data Products for Earthquake Hazards

Earthquake Catalog—ANSS Earthquake Catalog
http://www.quake.geo.berkeley.edu/anss/

This is the authoritative earthquake catalog for the United States. It contains the most current information from all of the participating regional networks and the U.S. National Network in the Advanced National Seismic System (ANSS). This catalog can be searched for a given geometric area, over a given time and a given magnitude range. Quarry blasts and earthquakes can also be selected/deselected. Earthquake time, location, magnitude, magnitude type, and parameters relating to how the earthquake location and magnitude were computed (number of stations, travel time error, and source network) are contained in the output of this search. This catalog contains all earthquakes that were detected by the local and regional networks within the United States, including both natural and induced earthquakes—if quarry blasts are not turned off, they will be included as well. This catalog reflects historical seismicity, which may be used as a guide to where we expect future seismicity, but there is always a possibility that earthquakes will occur where previous earthquakes have not. The catalog can be searched for earthquake-specific areas using the search tools at http://www.ncedc.org/anss/catalog-search.html. This catalog is updated in near-real time.

Caveats

- This earthquake catalog is not uniform. In some regions, the catalog begins much earlier than in others, because seismometers were deployed earlier.
- Detection capabilities are not uniform. As a seismic network becomes denser with time, it is able to record smaller earthquakes. This also means that regions with dense networks will see smaller earthquakes than regions with more sparse seismic networks.
- Earthquake locations and magnitudes are of varying quality. As the number of instruments close to the earthquakes increases, location and magnitude estimates become more accurate. This means that location and magnitude quality vary from region to region. Location and magnitude quality also vary over time within a region as the number of instruments increase.
- Earthquake magnitudes are computed a number of different ways depending on the earthquake size and number of nearby stations. These magnitudes are often similar, but not always the same.
- ANSS also maintains a webpage with caveats about their catalog: http://www.ncedc.org/anss/anss-caveats.html

An example of how increasing station density improves earthquake detection is found at the end of this document in the **USArray** section.

Earthquake Databases
http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

A variety of additional earthquake catalogs covering the U.S. are available online and can be used to search for both recent and historical earthquakes. An introduction to earthquake databases and catalog sources is available at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/database.php. Special attention should be paid to the explanation of differences between the various catalogs.

Online search tools that can be customized to select earthquakes in different geographic regions and over different time and magnitude ranges are available at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/.

Caveats

- These earthquake catalogs are not uniform in either space or time. In some regions, the catalog begins much earlier than in others because seismometers were deployed earlier.
- Earthquake smaller than magnitude 1 are not included in these catalogs.
- In most areas, the catalog is complete since 1973 for earthquakes of magnitude 3 or larger.
- The accuracy of the earthquake locations varies considerably. In most areas outside of California, Nevada, Oregon, Washington, and Utah, earthquake epicenters may be in error by as much as 6 miles, on average. Exceptions apply where there are local networks, such as in the New Madrid Seismic Zone.

National Seismic Hazard Map
http://earthquake.usgs.gov/hazards/products/

The National Seismic Hazard Map delineates the probability of strong shaking across the United States from natural earthquakes. These maps do not assess the risk of shaking owing to induced earthquakes. These are probabilistic maps and do not refer to specific earthquakes. Instead, the maps provide information on the strength of earthquake shaking that is unlikely to be exceeded over a given period of time.

A guide to the hazard maps can be found at:
http://earthquake.usgs.gov/hazards/about/basics.php

Frequently Asked Questions about Hazard Maps:
http://earthquake.usgs.gov/learn/faq/?categoryID=27

The maps are derived from knowledge of active faults, past earthquakes, and information on how seismic waves travel through the Earth. As indicated above, our knowledge of past earthquakes and faults is incomplete, which means that strong shaking due to earthquakes may still occur in regions with low probabilities. It is less likely to occur in these regions, but it still can happen.

The ground motions reported in these maps are estimated for the surface. Ground motions decrease with depth below the surface. Shaking is strongest in the area immediately surrounding an earthquake.

Earthquake Probability Calculator
https://geohazards.usgs.gov/eqprob/2009/index.php

This tool allows you to compute the probability of an earthquake occurring within a specific radius of a specified location. The probabilities are derived from the National Seismic Hazard Map described above. The tool produces two products:

1. A map surrounding the location specified, with color contours giving the probabilities of an earthquake larger than or equal to the magnitude specified by the user (minimum magnitude 5.0)

2. An optional text report describing the annual rates of earthquakes of different sizes.

It is important to note that, where the probability on the maps is shown to be 0.00, this does not mean that there will not be an earthquake there. When a region falls into the 0.00 category, it means that the probability of an earthquake is less than 1% during the time period specified.

By selecting the Text Report, it is possible to change the radius from the default value of 50 km. The Text Report gives information for earthquakes that fall within magnitude bins (for example, between 7.35 and 7.45): the annual rate at which an earthquake in that bin is expected to occur, the annual rate at which an earthquake within that bin or larger will occur, and probabilities of an event within that magnitude bin and within that bin or larger occurring in the time period specified by the user. The last two quantities can be inverted to determine the average number of years between earthquakes.

Limitations of the Probability Mapping Calculation
The probability is only calculated for events of M5 and larger. It is advisable to consider the rates of smaller earthquakes that may be the first evidence that an area is sensitive to injection-induced earthquakes. Such a calculation can be done using catalog searches but is not currently available as an online tool.

There are no confidence intervals on the probabilities. The values given are annual averages and earthquake rates naturally fluctuate in time. Therefore, as presently written, this application cannot help decide whether the seismicity in the last year, for example, is within the normal range of variation for this site.

The Quaternary Fault and Fold Database of the United States
http://earthquake.usgs.gov/hazards/qfaults/

This database contains information on known faults and associated folds in the United States that are believed to have been sources of M>6 earthquakes during the Quaternary (the past 1,600,000 years). The website includes both static and interactive maps of these geologic structures, with links to detailed references.

This database does not include faults that show no evidence of Quaternary movement. Faults that have had M>6 earthquakes but that do not extend to the surface and/or that have not been recognized at the surface may not be in the database. Only faults believed capable of hosting M>6 earthquakes are included, but earthquakes as small as M5 are potentially damaging, especially in the Central and Eastern U.S.

These considerations mean that, if the site is near a fault in the Quaternary Fault and Fold Database, then the necessary geologic structure exists to host an earthquake of M>6. However, if no fault in the database is near the site, it does not necessarily mean that no such fault is present.

New faults are continually being discovered, often as they reveal themselves by earthquake activity. Several years or more may pass between initial recognition that a fault is present, documentation in peer-reviewed literature that the fault is aerially extensive enough to produce a significant earthquake, and incorporation of the fault into the database. Changes to the Quaternary fault database are incorporated into the updates to the National Seismic Hazard Maps that occur every 6 years.

USArray—An Example of Improved Detection Capabilities From Increased Station Density
http://www.usarray.org/

As of this writing, a large seismic array of 400 instruments is moving across the conterminous U.S. This array, called USArray, is operated by the Incorporated Research Institutions for Seismology (IRIS) and is funded by the National Science Foundation as part of the EarthScope Program. During the 18 months that it takes for the USArray to pass by any particular location, the density of seismic stations is temporarily increased to one station approximately every
70 km, placing a seismometer within about 35 km of every point within the footprint of the array. This higher station density makes it possible to detect and locate earthquakes

with M≥2 in most areas and provides data that can be used to reduce the location uncertainty.
When USArray was passing through eastern Colorado and New Mexico from late 2008 to early 2010, several hundred events were detected that were not initially identified by the USGS. Many of these earthquakes lie within or near the coal-bed methane field west of Trinidad, CO.

The Oklahoma Geological Survey has recently used data from USArray to study earthquakes in Garvin County, Oklahoma, and their possible association with shale gas stimulation activities in the Eola Field (Holland, 2011). This report illustrates the potential of improved seismic monitoring for answering basic questions about the association between earthquakes and fluid injection activities. It also draws attention to the challenges of drawing firm conclusions when the historical context of the activity is poorly known and poorly resolved. The same general conclusions can be drawn from the study of earthquakes near Dallas-Fort Worth Airport (Frohlich, C., and others, 2011).

References Cited

Frohlich, C., Hayward, C., Stump B., and Potter, E., 2011, The Dallas-Fort Worth aarthquake sequence—October 2008 through May 2009: Bulletin of the Seismological Society of America, v. 101, p. 327–340.

Holland, A., 2011, Examination of possibly induced seismicity from hydraulic fracturing in the Eola Field, Garvin County, Oklahoma: Oklahoma Geological Survey Open-File Report F1-2011, 31 p.

The online tools described here are products of the U.S. Geological Survey, but no warranty, expressed or implied, can be provided for the accuracy or completeness of the data contained therein. These tools were not developed for the specific purpose of assessing the potential for induced seismicity and are not substitutes for the technical subject-matter knowledge.

Task 2.
Deep Stress Fields and Earthquakes Induced by Fluid Injection

Executive Summary

The purpose here is to explain what we know about deep stress fields and how this might influence the likelihood of earthquakes induced by injection well activities. The available evidence indicates that whether the tectonic setting is active (for example, near the San Andreas Fault in California) or inactive (for example, central or eastern United States), activities that entail injection of fluid at depth have some potential to induce earthquakes. This does not imply, however, that all injection-well activities induce earthquakes or that all earthquakes induced by injection activities are large enough to be of concern. Indeed, most injection wells do not appear to cause earthquakes of any consequence. The differences between the small percentage of wells that induce noticeable earthquakes and those that cause negligible seismicity are poorly understood. Thus, it is necessary to measure the response of the rock mass to injection to estimate the likelihood that a particular injection well will contribute to the local seismicity. An effective way to do this is seismic monitoring, using local networks that are capable of recording small-magnitude events. Furthermore, to evaluate the likelihood of inducing damaging earthquakes on large-scale, pre-existing faults, information is also needed on the geometry of potentially active faults in relation to the orientations and magnitudes of stresses at depth. This information can be obtained from network observations of ongoing micro-seismicity (if present), borehole stress measurements, and geophysical and geological investigations of fault geometry and fault-slip history.

Even in the absence of detailed information on stresses and fault geometry for a particular site, some useful generalizations can be made on the deep stress field. These generalizations are based on borehole stress measurements made around the world at depths of as much as 8 km, in conjunction with earthquake, geologic, and laboratory studies:

1. The stress field can be described in terms of three principal stresses that are oriented perpendicular to one another. To a good approximation, one of these principal stresses is vertical and the other two are horizontal.
2. The vertical principal stress is readily estimated because, at a given depth, it is due to the weight of the overlying rock mass.
3. The state of stress falls into three categories, depending on the relative magnitudes of the three principal stress regimes: normal, strike-slip, and reverse faulting, for which the vertical principal stress is the maximum, intermediate, or minimum principal stress, respectively. Studies of earthquake focal mechanisms, borehole stress indicators, and active faults have revealed the orientation of the principal crustal stresses at a broad, regional scale over most of the United States.
4. Stress measurements made in boreholes indicate that the horizontal principal stresses generally increase linearly with depth, similarly to the vertical principal stress, but sometimes with significant local perturbations.
5. For a given state of stress and depth, borehole stress measurements are generally consistent with laboratory friction experiments, which suggest that stresses are limited by the strength of the crust.
6. Observations that earthquakes, natural or man-made, may be induced by relatively small stress changes support the idea that the crust is commonly close to a state of failure.

Introduction

Of the approximately 144,000 Class II injection wells in the United States that inject large quantities of brine into the crust, only a small fraction of these wells induce earthquakes that are large enough to be of any consequence. In spite of their small numbers, these few cases raise concerns about the potential for significant damage resulting from larger induced earthquakes. Accordingly, it would be useful to have some guidelines concerning the likelihood that a particular well will cause significant earthquakes. The intent of Task 2 is to investigate the possibility that the deep stress field can be estimated from surface data. If so, then the next question is whether this stress information can be used to estimate the likelihood of substantial induced seismicity.

State of Stress

From information already available, we know the deep stress field to some extent. The stress field can be described as three principal stress components orthogonal to one another, with one component oriented vertically, perpendicular to the earth's surface, and the other two oriented horizontally. Factors including topography and geologic structure can alter these principal stress directions somewhat, but not on a large scale. The vertical principal stress at a given depth is, to a good approximation, the product of depth, gravity, and the average density between the surface and the point of interest. Because the approximate density structure of the crust is known nearly everywhere, the vertical principal stress can be readily estimated. Estimating the horizontal principal stress magnitudes requires more information, including knowledge of the local tectonic stress regime.

Surface data from seismograph stations or from observations of active faults and other stress indicators can reveal the tectonic stress regime, at least on a regional scale. This stress regime falls into three categories: normal faulting (vertical principal stress is maximum), strike-slip faulting (vertical principal stress is intermediate), or reverse faulting (vertical principal stress is minimum) (fig. 1). Earthquake focal mechanisms determined from ground motion recorded at seismograph stations indicate the stress regime wherever earthquakes occur, and, if properly analyzed, can provide valuable information on stress orientations (for example, Hardebeck and Michael, 2006). Geologic investigations of active faults, as well as geodetic measurements of crustal strain accumulation, provide similar information. Accordingly, from these sorts of investigations, which can be made from the surface, we know the regional tectonic stress

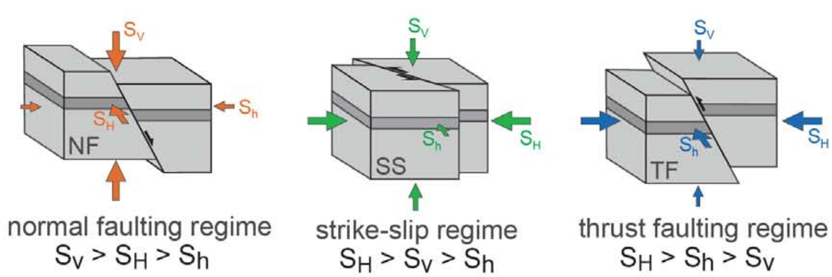


Figure 1. Schematic diagram showing tectonic stress regimes and sense of fault offset in relation to the vertical principal stress (S_V), the maximum horizontal principal stress (S_H), and the minimum horizontal principal stress (S_h) (from World Stress Map, cited below).

regime nearly everywhere in the United States and for much of the world (see World Stress Map, cited below). However, these observations only tell us the orientations and relative magnitudes of the horizontal principal stresses, and, hence, indicate whether we are in a normal, strike-slip, or reverse faulting stress regime. They do not tell us the absolute magnitudes of the horizontal stresses, which, together with information on stress orientations, determine proximity to failure on favorably oriented pre-existing faults.

Magnitudes of Horizontal Stresses

The question of the magnitudes of the horizontal stresses is more challenging. Most of our information about horizontal stress magnitudes comes from deep boreholes, using the hydraulic fracturing technique and observations of borehole failure (breakouts and tensile cracks; see Zoback and others, 2003). Additional stress data come from stress relaxation measurements made in deep mines. The deepest measurements were made in the KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) scientific borehole, eastern Bavaria, Germany, and extend to a depth of about 8 km (Brudy and others, 1997). Stress measurements worldwide indicate that the two horizontal principal stresses increase approximately linearly with depth, as is the case for the vertical stress. Moreover, in-situ stress magnitudes have been compared to laboratory experimental friction results (for example, Brace and Kohlstedt, 1980; Townend and Zoback, 2000) to find that the crust appears to be close to a failure state nearly everywhere. This experimental observation is consistent with the idea that the Earth's crust is extensively faulted and can deform by frictional sliding. Moreover, the crust is continually undergoing strain accumulation, at quite a slow rate in tectonically stable regions and at higher rates in tectonically active regions. The result of this long-term strain accumulation is that the crust is always near a failure state and releases strain whenever the yield stress is reached. In a seismogenic region of the crust (much of the uppermost ~15 km), this strain release appears as an earthquake sequence (mainshock and aftershocks). Other evidence in support of the hypothesis that the crust is near a state of failure nearly everywhere includes the observation that earthquakes can be triggered by remarkably small stress changes imposed on faults (for example, Reasenberg and Simpson, 1992).

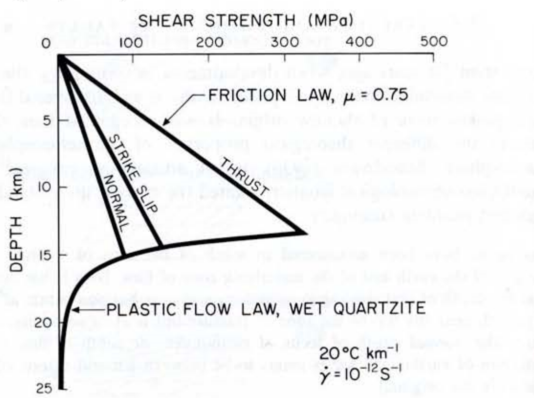


Figure 2. Shear strength of the crust based on laboratory friction experiments for the upper crust (upper 14 to 15 km) and experiments at high temperatures and pressures for the lower crust where deformation is ductile. The strength for strike-slip faulting can be anywhere between the reverse- and normal-faulting regimes. In this figure, shear strength is defined as the difference between the maximum and minimum principal stresses (from Scholz, 2002).

The laboratory friction results shown in figure 2 provide some information about the horizontal stress magnitudes. The line for a normal-faulting regime (labeled "normal") indicates the difference between the vertical principal stress and the minimum horizontal principal stress. For a reverse-faulting regime, the line shows the difference between the maximum horizontal principal stress and the vertical principal stress. Because the vertical stress can be readily estimated for any depth, as noted before, it is easy, from the information in the figure, to estimate the minimum principal stress for the normal-faulting regime and the maximum principal stress for the reverse-faulting regime. For a strike-slip regime, neither horizontal principal stress can be inferred because the line labeled "strike slip" can fall anywhere between those for normal and reverse regimes. Although generalizations can be drawn about proximity of the crust to failure from this type of analysis, it is important to note that for a particular fault to be activated in response to fluid injection requires that it be well oriented for frictional failure in the local tectonic stress field.

In brief summary, we know that the vertical principal stress can be calculated for any depth, and we also know that laboratory friction experiments (fig. 1) are reasonably consistent with in-situ stress measurements in deep boreholes. These deep borehole measurements, in concert with the observation that earthquakes can be triggered at low applied stresses, indicates that the crust is near a failure state nearly everywhere. Taken together, this information can be used to estimate, at least approximately, the magnitudes of the maximum and minimum principal stresses at depth that are valid for most rock types for normal- and reverse-faulting regimes; for strike-slip regimes, the maximum and minimum principal stresses fall somewhere in the range between the normal and reverse results. If direct information on stress orientations is lacking for a particular area, then the orientations of the horizontal principal stresses can be estimated by comparison with nearby data that might be available through the World Stress Map Project (http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction_frame.html).

Conclusions

Because the state of stress in much of the Earth's crust appears to be close to failure, the safest assumption is that any amount of fluid injection could produce some earthquakes. Knowing that it may be possible to induce some earthquakes, however, is not enough. It is also important to be able to estimate the maximum likely earthquake that might be induced by a particular injection operation and measure the seismic response of the rock mass to injection. That is, one needs to be able to estimate the distribution of earthquake magnitudes, including the maximum magnitude, likely to result from a given injection activity. To accomplish this goal, it is first recommended to determine the in-situ stress field in relation to the orientation and extent of potentially active faults, especially large faults capable of producing damaging earthquakes (fig. 1). Then, in order to monitor the injection disposal operation, a local seismic network should be installed before commencement of injection that is capable of recording and locating earthquakes over a wide magnitude range. Monitoring induced earthquakes in this way will allow comparison with the injection-time history, as well as with background seismicity, and will also help define the subsurface geometry of large-scale active faults that comprise the greatest hazard. With information provided by a seismic network, the contribution of the induced earthquakes to the ambient seismic hazard can be assessed.

References Cited

Brace, W.F., and Kohlstedt, D.L, 1980, Limits on lithospheric stress imposed by laboratory experiments: Journal of Geophysical Research, v. 85, p. 6248–6252.

Brudy, M., Zoback, M.D., Fuchs, K., Rummel, F., and Baumgartner, J., 1997, Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes—Implications for crustal strength: Journal of Geophysical Research, v. 102, p. 18,453–18,475.

Hardebeck, J.L., and Michael, A.J., 2006, Damped regional-scale stress inversions—Methodology and examples for southern California and the Coalinga aftershock sequence: Journal of Geophysical Research, v. 111, B11310, doi:10.1029/2005JB004144.

Reasenberg, P.A., and Simpson, R.W., 1992, Response of regional seismicity to the static stress change produced by the Loma Prieta earthquake: Science, v. 255, p. 1687–1690.

Scholz, C.H., 2002, The mechanics of earthquakes and faulting: Cambridge University Press, 471 p.

Townend, J., and Zoback, M.D., 2000, How faulting keeps the crust strong: Geology, v. 28, no. 5, p. 399–402.

Zoback, M.D., Barton, C., Brudy, M., Castillo, D., Finkbeiner, T., Grollimund, B., Moos, D., Peska, P., Ward, C., and Wiprut, D., 2003, Determination of stress orientation and magnitude in deep wells: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 40, p. 1049–1076.